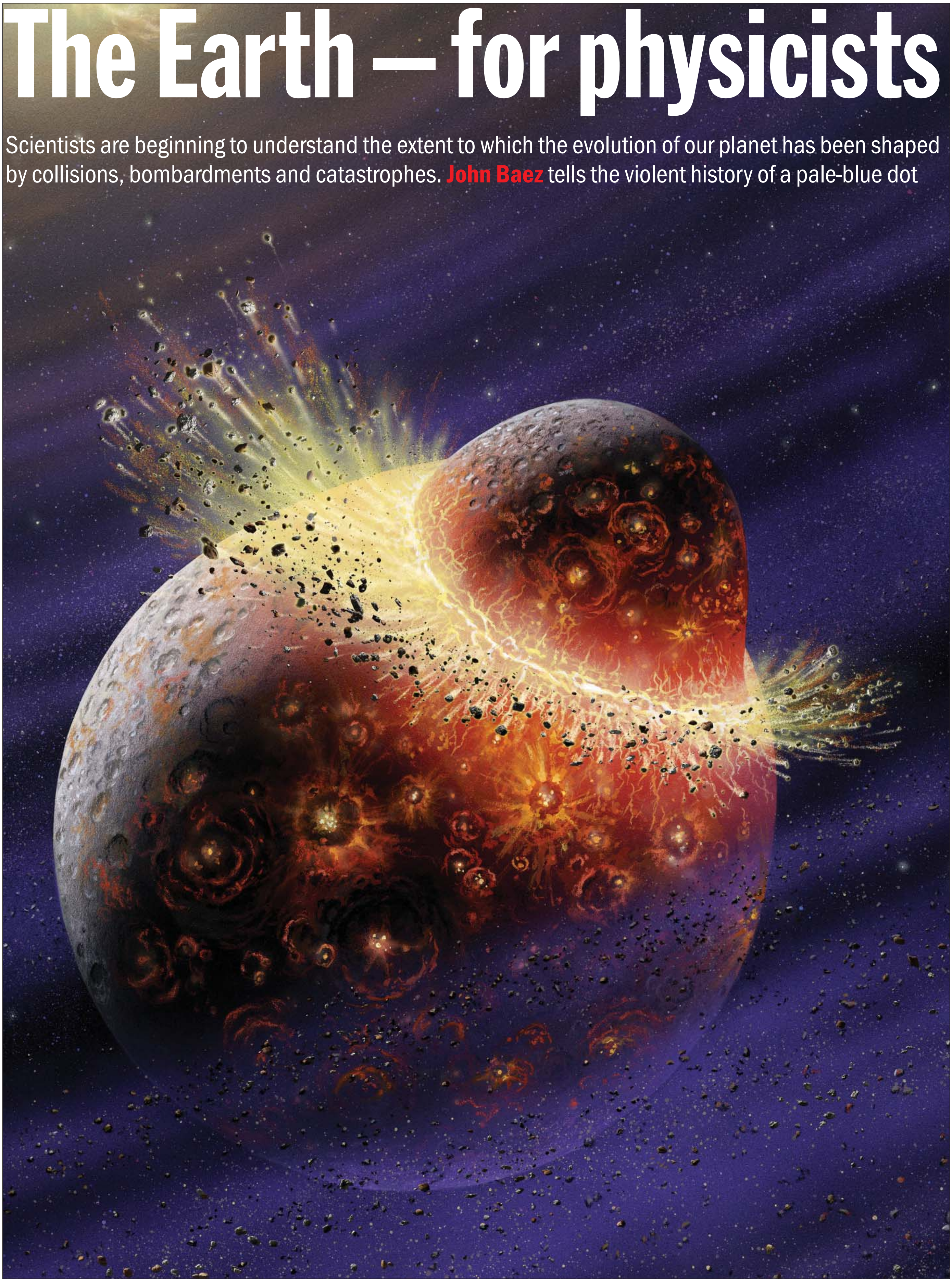
The Earth – for physicists

Scientists are beginning to understand the extent to which the evolution of our planet has been shaped by collisions, bombardments and catastrophes. **John Baez** tells the violent history of a pale-blue dot



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The prospect of human-induced climate change has many people worried. In addition to the sheer scale of the problem, there is also the challenge of it being so complex. The Earth's behaviour is fiendishly hard to predict in detail. Computer power is not enough: models need to be based on solid physical insights and a good understanding of the Earth's current behaviour – and also its *history*.

Luckily, in the past decade we have learned a vast amount about this history. The mists of time are clearing. It seems we are not alone in passing through perilous times. The Earth has witnessed some remarkable disasters. To keep our tale brief, let us focus on four: the "big splat" about 4.55 billion years ago; the "late heavy bombardment" about 4 billion years ago; the "oxygen catastrophe" roughly 2.5 billion years ago; and the "snowball Earth" events about 850 million years ago. The details of these events – and indeed whether they even happened at all – remain controversial. They are, however, widely accepted theories. In every case there is interesting physics involved in testing these theories.

The birth of the Moon

The Sun was probably formed from the gravitational collapse of a cloud of gas and dust. Early models of star formation assumed spherical symmetry, but if you know the joke to which the punchline is "consider a spherical cow", then you should suspect that this is a dangerous oversimplification. Indeed, angular momentum plays a major role. As such a cloud collapses gravitationally, it should form a spinning "accretion disk".

When the centre of this disk became dense enough for its pressure to hold it up, our Sun was born as a "protostar". This phase lasted a scant 100 000 years or so; the temperature then rose to the point where an outflow of hot gas prevented the Sun from accreting any more material. At this point the Sun became what we call a "T Tauri star", powered only by gravitational energy as it slowly shrank. After about a further 100 million years, it became an ordinary main-sequence star as the hydrogen at its core began to undergo fusion.

Some dust circling the early Sun became hot and melted, and some of the molten droplets later froze into "chondrules" – millimetre-sized spheres of simple minerals such as pyroxene and olivine, which are mostly made of sodium, calcium, magnesium, aluminium, iron, silicon and oxygen. These chondrules are the main constituent of some of the most primitive objects that still ply their way through the solar system: stony meteorites called "chondrites".

The dust circling the early Sun started forming lumps called "planetesimals". As these lumps collided, they got bigger and bigger, eventually forming the asteroids and planets we see today. Some lumps melted, letting heavier metals sink to their cores while lighter material stayed on the surface. And some crashed into each other, shattering and forming chondrites and other meteorites such as iron–nickel meteorites and stony meteorites called "achondrites".

By using radioactive-dating techniques on meteorites, researchers claim a shockingly precise knowledge of when all this happened: sometime between 4.56 and 4.55 billion years ago. So, the Earth was probably formed sometime around then – and our story officially begins at this point.

The Earth's history is divided into four eons: Hadean, Archean, Proterozoic and Phanerozoic. When I was a child, the "Cambrian era" was as far back as my textbooks went, except for the murky "Precambrian". But the Cambrian began just 540 million years ago. The Cambrian marks the start of the current eon, the Phanerozoic, meaning "the age of visible life". This is when multicellular organisms took over the world, leaving fossils we find today. But we will dig much deeper: the Phanerozoic will be *end* of our story.

Back to the Hadean. As befits its name, this was a time when the Earth was hellishly hot. It began with an event that formed the Moon around 4.53 billion years ago. What made the Moon? The most popular current explanation is the "giant-impact theory" – sometimes called the "big splat" theory.

The idea is that another planet formed at one of the Lagrange points of Earth's orbit. In 1772 Joseph Louis Lagrange showed that if you have a planet in a circular orbit about the Sun, then a much lighter body will stably orbit the Sun at the same distance if it lies 60° ahead or behind that planet. There are indeed many asteroids located near the Lagrange points of Jupiter, and also some at the Lagrange points of Mars and Neptune.

No asteroids have been found at Earth's Lagrange points. But according to the giant-impact theory, a planet did form at one of these points. When it attained a mass of about that of Mars, it would no longer have been stable at this location. It would have gradually drifted toward the Earth, and eventually smacked right into it! This collision could have formed the Moon.

It is a dramatic theory, but there is a strong case for it, nicely summarized by science writer Dana Mackenzie's recent book *The Big Splat, Or How Our Moon Came to Be*. For example, tidal friction is making the Moon gradually recede from the Earth. We know it is now moving away at a rate of about 3.8 cm per year. Ancient sediments record the tides and show that months have been getting longer at least since Precambrian times. Extrapolating backwards we find that in the Hadean eon the Moon was very close to the Earth. Could it have been flung off from the Earth by centrifugal force, or formed near the Earth in the first place, or captured by the Earth's gravitational field? All these theories must be considered, but the giant-impact theory seems to fit the data best. People take it so seriously that the hypothetical doomed planet that hit Earth even has a name: Theia. In Greek mythology, Theia was a female titan who gave birth to the Moon.

In 2004 the astrophysicist Robin Canup of the Southwest Research Institute in Boulder, Colorado, published some remarkable computer simulations of

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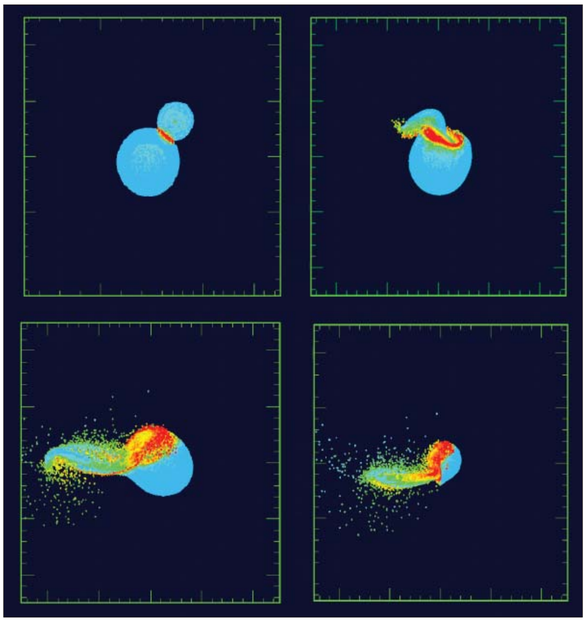


A very bad day A computer simulation showing the collision between Theia and the Earth. According to the "big splat" theory, Theia was a planet that formed at the Earth's Lagrange point. As a result of this planetary crash, the Moon was formed.

Robin Canup, Southwest Research Institute

the big splat. To get a moon like ours to form – instead of one that is too rich in iron, or too small, or wrong in other respects – you need to choose the right initial conditions. Canup found it best to assume that Theia is slightly more massive than Mars: between 10% and 15% of the Earth's mass. It should also start out moving slowly towards the Earth, and strike the Earth at a glancing angle.

The result is a *very* bad day. Theia hits the Earth and shears off a large chunk, forming a trail of shattered, molten or vaporized rock that arcs off into space. Within an hour, half the Earth's surface is red hot, and the trail of debris stretches almost four Earth radii into space. After three to five hours, the iron core of Theia and most of the debris comes crashing down. The Earth's entire crust and outer mantle melts. At this point, a quarter of Theia has actually vaporized.

After a day, the material that has not fallen back down has formed a ring of debris orbiting the Earth. But such a ring would not be stable: within a century, it would have collect to form the Moon we know and love. Meanwhile, Theia's iron core would have sunk to the centre of the Earth.

The giant-impact theory is still much debated, in part because there is little direct evidence left: the oldest known rocks on Earth were formed almost half a billion years later.

Meteor impacts of the size that may have killed off the dinosaurs would have been routine during the late heavy bombardment

The late heavy bombardment

The Archean eon begins with the formation of the first rocks that survive to this day. This happened about 4 billion years ago. Many igneous rocks, in particular basalt, must have been formed before this. In fact, the oceans may have started forming 4.2 billion years ago. But we do not see any traces of this early geology. One possible reason is that the beginning of the Archean eon was not a peaceful time.

After the Moon was formed, the Earth continued to suffer many impacts. Curiously, instead of their frequency gradually dropping off over time, it may have spiked during a period called the late heavy bombardment, which occurred some 4 to 3.8 billion years ago. A lot of large craters on the Moon date back to this period, so probably the Earth got hit too – but here, such old craters would be lost to weathering and geological activity. So, the Moon is our guide.

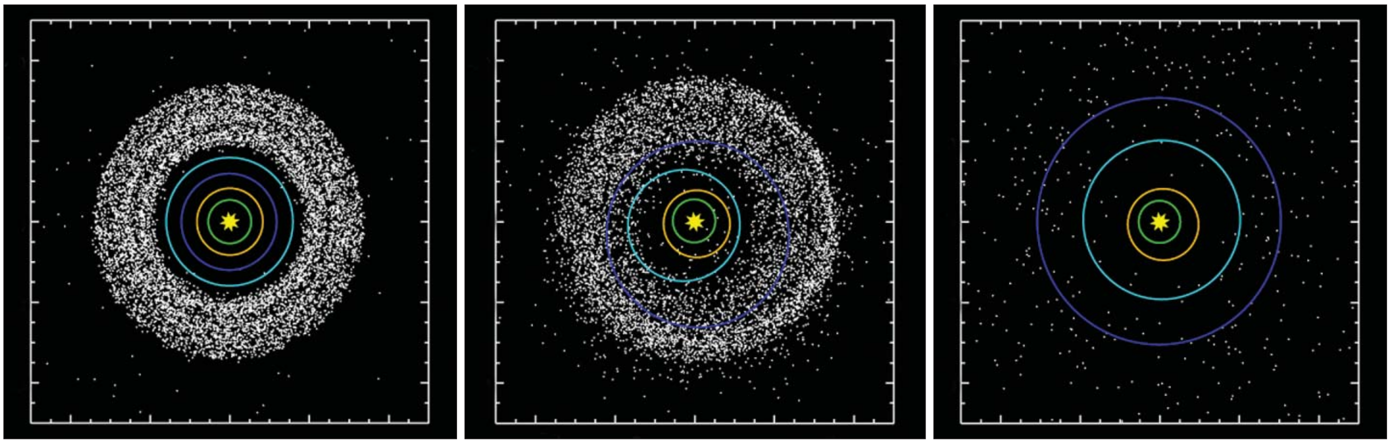
During the late heavy bombardment, the Moon was hit by 1700 meteors that made craters that are more than 100 km across. The Earth could easily have received 10 times as many impacts of this size, with some being much larger. To get a sense of the intensity of this pummelling, recall the meteor impact that may have killed off the dinosaurs at the end of the Cretaceous period 65 million years ago. This left a crater 180 km across. Impacts of this size would have been routine during the late heavy bombardment.

Why was this era so violent? One theory is that at around this time Jupiter and Saturn moved into a 2:1 orbital resonance (when Jupiter completes two orbits at the same time as Saturn completes just one), thereby causing a big disruption in the original population of asteroids and icy objects orbiting the Sun. In 2005 an international collaboration of planetary physicists, including Hal Levison from Southwest Research Institute – one of the people who pushed the idea that Pluto is a "dwarf planet" – published a paper about some fascinating computer simulations of the solar system (*Nature* **435** 466). As initial conditions, they take all four gas giants to lie in circular orbits more closely spaced than they are now. By interacting with planetesimals, Saturn, Uranus and Neptune gradually migrate outwards. When Saturn reaches the point where it orbits the Sun once for every two orbits of Jupiter, the whole outer solar system destabilizes. The orbits of Neptune and Uranus become more eccentric and they throw many planetesimals out of their original orbits. Some are hurled into the inner solar system, which would explain the late heavy bombardment.

The oxygen catastrophe

It is believed that the Earth's surface cooled enough to form a crust even before the late heavy bombardment. Meanwhile, volcanic activity would have released lots of steam, carbon dioxide and ammonia. This formed what is called the Earth's "second atmosphere". The Earth's "first atmosphere", mainly hydrogen and helium, was already lost to space. The second atmosphere was mainly carbon dioxide and water vapour, with some nitrogen but probably not much oxygen. This second atmosphere had about 100 times as much gas as today's "third atmosphere".

As the Earth cooled, oceans formed. They may have boiled away completely during some large impacts but then reformed. Eventually much of the carbon dioxide in the atmosphere dissolved into the seawater. This later precipitated out as carbonates, thus starting a new phase in what the geologist Robert Hazen of the Carnegie Institution of Washington's Geophysical Laboratory and his co-workers call "mineral evolution". This is not evolution in the Darwinian sense, just the gradual diversification of minerals over the Earth's history. In 2008 a team of geologists led by Hazen estimated that



Mark Wyatt, University of Cambridge

Meteor blitz A computer simulation showing outer planets – Jupiter (green), Saturn (orange), Uranus (light blue) and Neptune (dark blue) – and the Kuiper belt before the Jupiter/Saturn 2:1 orbit resonance (left), while scattering Kuiper-belt objects into the solar system after the orbital shift of Neptune (middle), and after the ejection of Kuiper-belt bodies by Jupiter (right).

350 kinds of mineral could be found on Earth during the Hadean eon. But as the Earth's history proceeds, their count keeps rising. By the end of the Archean eon it reaches 1500, thanks in part to the formation of oceans – but also thanks to the rise of plate tectonics.

The first step in plate tectonics was the formation of "cratons": ancient, tightly knit pieces of the Earth's crust and mantle, dozens of which survive today. For example, in the UK, south-eastern Wales and part of western England lie in the Midlands craton. While most cratons only finished forming 2.7 billion years ago, nearly all started growing earlier. Cratons are made largely of igneous rocks like granite, which are more sophisticated than basalt. Granite is formed in a variety of ways, for example by the remelting of sedimentary rock. Early granite-like rocks were probably simpler.

Cratons fit together to form the larger plates that constitute the Earth's crust today. Indeed, plate tectonics as we know it started about three billion years ago. A key aspect of this process is the recycling of the Earth's crust through "subduction": oceanic plates slide under continental plates and get pushed down into the mantle. Another feature is underwater volcanism, leading to hydrothermal vents – fissures in the seafloor that spew out hot water.

It is possible that these vents played a role in the most dramatic of all Archean developments: the origin of life. Since the early Earth lacked free oxygen, the first life must have been anaerobic. Even today, many of the oldest known microbes, such as those found in hydrothermal vents, cannot tolerate the presence of oxygen. Such organisms gave rise to an active sulphur cycle and deposits of sulphate ores starting about 3.6 billion years ago. Later they made the atmosphere increasingly rich in methane.

At some point, microbes started photosynthesizing and putting oxygen into the atmosphere. It seems likely that the first plants acquired their ability to photosynthesize by symbiosis with such microbes. Indeed, the chloroplasts in plants have their own separate DNA.

It is not clear when photosynthesis began – estimates range between 3.5 and 2.6 billion years ago. One possible clue – rocks called "banded iron formations" that are made of thin layers of iron oxides alternating with iron-poor rock – started to appear at about this time. They may have formed when oxygen from the first photosynthesizing organisms reacted with iron in seawater. No-one knows for sure why the periods of iron-rich sediment come and go.

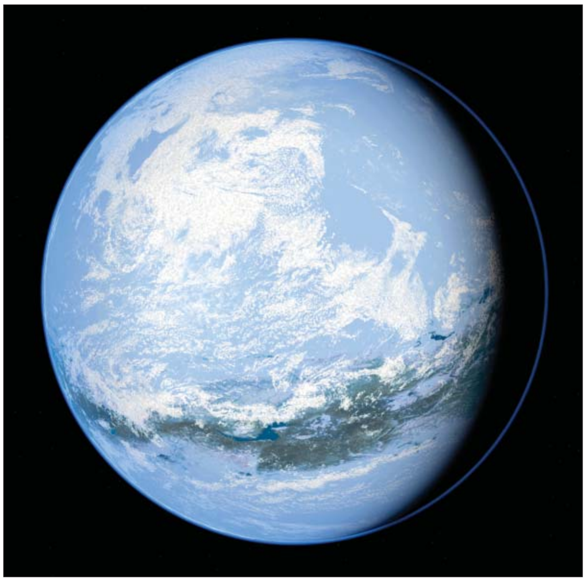
It took a long time for photosynthesis to have a significant effect on the Earth's atmosphere – but when they did, roughly 2.5 billion years ago, the result was dramatic. After all, oxygen is highly reactive in its gaseous form, and most early life could not tolerate it. So, this episode in the Earth's history has been dubbed the oxygen catastrophe. Luckily, evolution found a way out: now many species need oxygen.

The oxygen catastrophe marks the end of the Archean eon and the beginning of a new eon, the Proterozoic. The next billion years were dominated by something called the "intermediate ocean": the seawater contained a lot more oxygen than before, but still much less than today.

Snowball Earth

Starting about 850 million years ago, something dramatic happened: episodes of runaway glaciation during which most or all the Earth was covered with ice. Advocates of the extreme version of this scenario call them "snowball Earth" events, while others argue for a mere "slushball". Since ice reflects sunlight, making the Earth even colder, it is easy to guess how such runaway feedback might happen. The opposite sort of feedback is happening now, as melting ice makes the Earth darker and thus even warmer. The interesting questions are why this instability does not keep driving the Earth to extreme temperatures one way or another, why the snowball-Earth events started when they did, and why the Earth did not stay frozen.

Here is a currently popular answer to the last question. Ice sheets slow down the weathering of rock. This weathering is one of the main long-term processes that use up atmospheric carbon dioxide, by converting it into various carbonate minerals. On the other hand, even on an ice-covered Earth, volcanic activity would keep putting carbon dioxide into the atmosphere. So, eventually carbon dioxide would build up and the greenhouse effect would warm things up again. When the ice melted, weathering would increase and the amount of carbon dioxide in the atmosphere would



Simon Terrey/Science Photo Library

The big chill
According to the "snowball Earth" hypothesis, 850 million years ago our planet's surface was completely frozen.

drop again. However, this feedback loop is very slow. Indeed, it has been suggested that in the hot phase, as much as 13% of the atmosphere could be carbon dioxide – some 350 times more than we see today!

By the end of these glacial cycles, it is believed that oxygen had increased from 2% of the atmosphere to 15%. (Now it is 21%.) This may be why multicelled oxygen-breathing organisms date back to this time. Others argue that the "freeze–fry" cycle imposed tremendous evolutionary pressure on life and led to the rise of multicellular organisms. Both these theories could be correct. (For more details, try Gabrielle Walker's excellent book *Snowball Earth*.)

The rise of multicellular organisms marks the end of the Proterozoic eon and the start of the current eon: the Phanerozoic. This is the end of our story – but of course the history of the Earth does not end here.

We are now in the Cenozoic era of the Phanerozoic eon. The Holocene era has just ended and the Anthropocene has begun, characterized by significant human impact on ecosystems and climate. By demolishing natural habitats, humans have set in motion a mass-extinction event that may rank with the end of the Cretaceous period 65 million years ago. We are also boosting atmospheric carbon-dioxide levels at an incredible rate. If the temperature rises by one more degree, then the Earth's temperature will be the hottest it has been in 1.35 million years, before the current cycle of ice ages began. Where are we heading? Nobody knows.

However, studying the history of the Earth will put us in a better position to guess. We cannot run experiments to test the Earth's response to different levels of greenhouse gases. Computer models are essential, but evidence from snowball Earth and other incidents in the Earth's past are crucial checks on these models. Similarly, studying past mass-extinction events, and the Earth's recovery from them, may provide clues about the future of biodiversity on this planet.