Under a cold sun

How did life on Earth get started, when our young planet should have been frozen and inhospitable? **Stuart Clark** investigates

WHY are we here? As questions go, it's a big 'un, beloved of philosophers and theologists in a navel-gazing, hand-wringing sort of way. Scientists often find themselves raising an objection before the others even start: we probably shouldn't be here to ask the question in the first place.

The existence of life on Earth seems to have been the product of many lucky turns of events. Take the sun's early history. According to everything we know about how stars like it develop, it should have been born feebly dim, only gradually warming to its present level. Earth, born with the sun 4.5 billion years ago, should have spent its first 2 billion years or so as a frozen ball of ice, devoid of life.

Yet in rocks laid down during this time we find sediments clearly deposited in aquatic environments, and ample fossil evidence of bacteria that indicate our planet was already a clement, inhabited world, perhaps within a billion years or so from the off. This mismatch, known as the faint young sun paradox, has many potential solutions. None quite has the ring of truth. But as suggestions accumulate and are discarded, one conclusion seems ever harder to ignore: we are even luckier to be here than we thought.

The faint young sun paradox has its origins in the 1960s, when astrophysicists ran the first crude computer simulations of how changes in chemical composition affect the luminosity and heat output of stars such as our sun. The results were clear: the greater abundance of hydrogen in the early sun's core would have given it a higher internal pressure, expanding the star's nuclear heart and lowering its temperature. As a result, the sun's output in its early years was 25 to 30 per cent lower than it is today. That translates into an average surface temperature of the early Earth some 20 degrees cooler –

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about 10 degrees below water's freezing point.

Yet records of liquid water on Earth go back almost as far as the planet itself. Deposits of the mineral zircon in rocks from Jack Hills in Western Australia have been dated to 4.4 billion years ago, and contain oxygen isotopes that point to their having formed in a watery environment. In the same region there are fossil stromatolites, layered structures formed in shallow water by microbial communities, thought to date to 3.5 billion years ago.

"This clearly tells us that simple models for planetary habitability are wrong," says David Minton, a planetary scientist at Purdue University in West Lafayette, Indiana. "There was life on Earth when it should have been a frozen wasteland." Minton was one of a few dozen astrophysicists and geophysicists who met in Baltimore, Maryland, in 2012 to discuss ways out of this bind. "It turned out that there were almost as many potential solutions as there were participants," he says.

An early proposal is still the most popular: that some greenhouse gas allowed the early Earth's atmosphere to trap more of the weak sun's rays. The suggestion was first made in 1972 in *Science* by astronomers Carl Sagan and George Mullen. But as they discovered, finding the right gas is tricky.

Correct cocktails

Carbon dioxide seems unlikely to be the sole culprit. CO_2 enters soil either in raindrops or through direct diffusion, and drives chemical weathering that is reflected in the mineral composition of rocks known as palaeosols. Studies of ancient palaeosols do suggest atmospheric CO_2 levels were higher back in the Archean era, which ran from 3.8 billion years ago to 2.5 billion years ago. But to keep the oceans at a surely liquid temperature of 5 degrees above freezing, they would need to be some 300 times the current amount – 10 times more than even the most generous palaeosol estimates.

James Kasting, a palaeoclimatologist at Penn State University in Philadelphia, still thinks a CO_2-based greenhouse effect is the solution, pointing to other evidence of its role in mediating Earth's temperature (see "Carbon control", page 23). "I pay attention to those estimates even if I don't completely agree with some them," he says. All that is needed is to find the correct cocktail of other gases that was mixed in with the CO_2.

Back in 1972, Sagan and Mullen suggested ammonia and methane. But ammonia is highly susceptible to ultraviolet light and, with no protective ozone layer around the early Earth, would have been destroyed easily even by the faint young sun's rays. Methane is a powerful greenhouse gas but above a certain ›

"Atmospheric composition, rotation, albedo, the effect of clouds could all be the answer – or they could be red herrings"

concentration forms an organic haze that absorbs sunlight, radiating it back into space. Too much methane cools a planet's surface instead of warming it – an effect astronomers have seen on Saturn's moon Titan.

Titan suggests other ways of making Earth's early atmosphere more of a comforting blanket. While at the University of Chicago in 2013, Robin Wordsworth and Raymond Pierrehumbert, investigated whether high levels of nitrogen and hydrogen, such as are found on Titan, can have a warming effect. While the answer is yes, there is no evidence that Earth's atmosphere was ever dense enough to hold the required quantities.

"It turns out that all the gases are more problematic than you hope," says Georg Feulner of the Potsdam Institute for Climate Impact Research in Germany. He believes one reason the paradox has yet to be resolved is that the computer models generally used to study ancient climates are too crude to provide meaningful results.

Relentless activity

The models are crude because they typically ignore factors such as Earth's rotation, which has slowed over the years owing to the effect of the moon's gravity. This slowing would have altered the pattern of heat transport from the equator to the poles, perhaps changing the extent of ice cover and so the amount of energy that was reflected straight back up into space rather than being absorbed by Earth.

This quantity, the albedo, is a general problem. "We know nothing at all about the albedo of the early Earth," says Kasting. Oceans tend to absorb more heat than land does, so the albedo will be affected by factors such as the arrangement of the continents. Thanks to Earth's relentless tectonic activity, this would have been very different in the distant past. Minik Rosing and his colleagues at the University of Copenhagen, Denmark, have even controversially argued that considerably reduced continental cover, plus chemical differences in cloud cover, would have reduced the albedo enough to explain the faint young sun paradox without the need to invoke higher levels of greenhouse gases at all.

All of these factors – atmospheric composition, rotation, albedo, the effect of clouds – could be the key to solving the paradox. Or they could be red herrings. We simply do not know. Feulner's own latest attempt at a more sophisticated climate model (albeit with a simplified atmosphere) suggests that previous studies have underestimated the cooling effects of faster rotation and ice cover, making the faint young sun paradox even more of a problem. However, other studies using sophisticated atmosphere models but without the important effects of ocean and sea-ice dynamics, did not find this.

A few years down the line, he hopes to bring together the teams working on simulations of the early Earth's climate to compare results. That way they can see which effects are a result of the theoretical assumptions that go into making individual models. Any warming effects that pop up in all models, regardless of the assumptions, stand a greater chance of being the key to the problem.

Meanwhile some geophysicists continue to cast a suspicious eye at the sun. Is it possible that astrophysicists have not got the workings of our star nailed down? "Every 10 years or so, someone proposes that the sun must have been more massive in the past," says Kasting. The excess would have to have been substantial – about 2.5 per cent, or 8250 Earth masses – to have made the sun shine brightly enough. Although the sun is constantly flinging particles into space, creating the solar wind, it currently takes 150 million years to lose the mass equivalent to a single Earth. That means the solar wind must have been stronger in the past – a great deal stronger. "That's a sustained mass loss which is at least 10 times larger than anything we infer through the observation of other stars," says Minton.

The book is not closed on all astronomical suggestions. Minton's own involves a game of planetary billiards, and is inspired by the work of Jacques Laskar of the Paris Observatory in France. In 2009, Laskar made headlines with a series of computer simulations that showed that the orbits of the solar system's inner planets are not necessarily stable over billions of years. In one particularly alarming scenario, the gravity of the outer solar system's giant, Jupiter, might destabilise Mercury's orbit, flinging it outwards and potentially causing collisions between it, Venus, Earth and Mars in about 3.5 billion years' time.

Orbital shift

Minton thinks what may be possible in the future could also be true of the past. He investigated what it would have taken for Earth to form closer to the sun and only move out to its present orbit later, neatly solving the faint young sun paradox. In work yet to be published, he has found that it would not have taken much. "You only need to change the orbit of Earth by a few per cent," he says. Even

Five ways to a warmer Earth

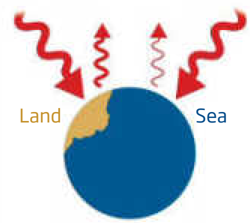
For its first two billion years or so the sun should not have been warm enough to make Earth hospitable to life. Many solutions have been proposed to this paradox - but all have their own problems

A HOTTER GREENHOUSE

A more powerful blanket of greenhouse gases around the early Earth trapped more heat

PROBLEM Which gases?

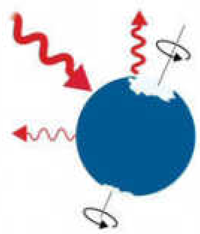
HIGHER ALBEDO



Land reflects more heat than ocean – so if the early Earth had more ocean cover it would have retained more heat

PROBLEM How do you test it?

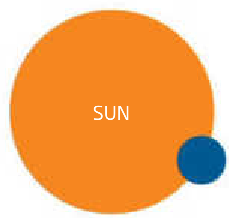
FASTER ROTATION



Earth's faster past spinning could have transferred heat to the poles more quickly than today, melting reflective ice there

PROBLEM Effect is too small on its own

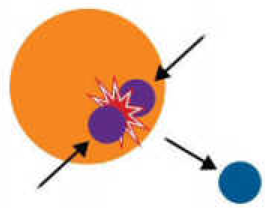
A BIGGER SUN



The early sun was more massive to compensate for its lower luminosity

PROBLEM Where did all that extra mass go?

PLANETARY BILLIARDS



A collision of two other planets nudged Earth out of a warm nursery closer to the sun

PROBLEM No evidence

so, such an orbital shift is something that is easier to make happen with a catastrophe, rather than gradually. The catastrophe Minton imagined was a collision between two planets about 2.5 billion years ago that created the present-day Venus. The resulting small change in the gravitational environment would have been enough to nudge Earth outwards to its present location, ensuring that as the sun warmed up, life on Earth did not roast.

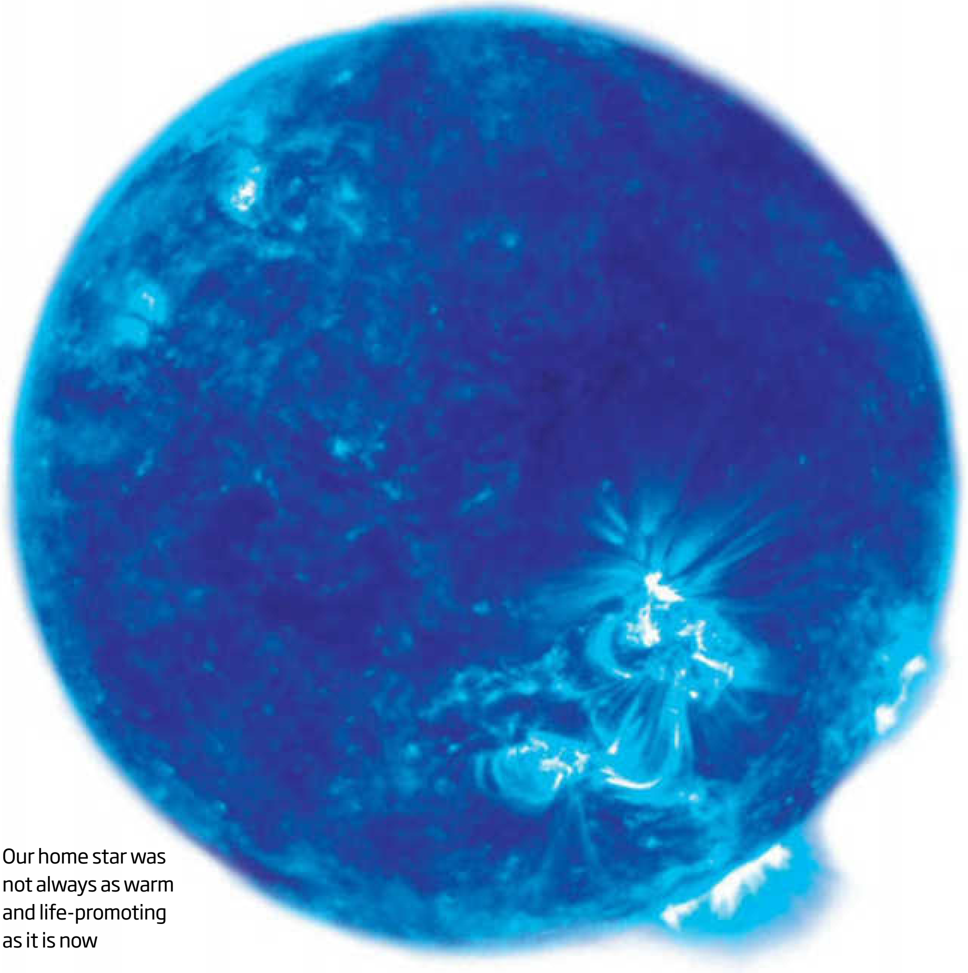
Even Minton admits the idea is a little wacky – and almost impossible to test. A planet's age can often be estimated by the density of craters on its face, but those on Venus are hidden well. A simple count of its craters suggests a figure of just 500 million to a billion years – far too young to be a plausible age under any scenario. Something must have happened to Venus's surface to smooth out earlier wrinkles. Until we work out what, we are at a loss to work out the planet's true age.

Kasting, too, is sceptical of Minton's idea, and invokes Occam's razor. "You should keep solutions simple," he says. Unfortunately, simple solutions are what we currently lack. Indeed, all the indications are that no single factor can explain away the faint young sun paradox. And that raises a wider question. If Earth's habitability is indeed a product of a finely tuned combination of events, how many other planets have been able to tread a similarly unlikely path?

Feulner shrugs off the question, saying we need to put our own house in order before going on to speculate about other worlds. "As our understanding of ancient climates is still so preliminary, I'd be happy to understand the solution to the faint young sun paradox first, and then wonder about the consequences."

Minton takes a different view. If there are many feasible solutions to the paradox – even if only one of them can be true for the Earth – others could be playing out on other planets around the galaxy. The many different ways to achieve habitability may overwhelm the implausibility of any single solution. "There may be so many complicating factors that the whole thing just opens up," he says. "Biospheres may be much more robust than we think, and planetary environments we currently consider to be utterly hostile could themselves be perfectly hospitable."

For those prone to loneliness and existential angst that is perhaps a comforting thought. Although it still doesn't answer the question: why *are* we here? ■



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Our home star was not always as warm and life-promoting as it is now

Carbon control

All the evidence suggests that Earth's Archean era, which ended 2.5 billion years ago, was substantially warmer than models of the sun's early development allow (see main story), But there is no doubt as to how the era ended: our planet abruptly chilled into its first ice age. Known as the Huronian glaciation, this was one of the longest, most severe ice ages in Earth's history - and it took place just when the sun should have been reaching temperatures capable of turning our planet into a clement world. Why?

James Kasting of Penn State University in Philadelphia points to a possible culprit: life - in particular the oxygen given out by the first photosynthesising bacteria. Oxygen tears apart methane, a powerful greenhouse gas, to create carbon dioxide and water. "Before the rise of oxygen, methane was stable in the atmosphere for 10,000 years," he says. Afterwards, the average molecule lasted just a decade or so. Methane is a much more efficient greenhouse gas than the CO_2 created in this process, so Earth cooled.

But how then did our planet escape its ice age again? The answer probably lies in how atmospheric CO_2 dissolves in rainwater and enters soils, chemically weathering the existing rocks and building carbonate minerals that are eventually taken deep into the Earth through tectonic action. After many millions of years, volcanoes reprocess these rocks and return the CO_2 to the atmosphere as part of their gaseous outpourings.

When temperatures drop, as at the start of the Huronian glaciation, chemical weathering slows down because the chemistry involved is partly driven by temperature, but the volcanoes continue to release the previously stored CO_2. This builds a larger greenhouse effect, boosting the temperature and ending the ice age.

Such effects convince Kasting that the regulatory role of CO_2 holds the key to the faint young sun paradox. "Carbon dioxide will always tend to rise to a level that keeps the Earth from freezing," he says.