Stuart Clark

The Sun: Diary of a death

Every day we take the warmth and light of our Sun for granted. But what if we were to discover that this plentiful font of energy was dying? That's the premise behind Sunshine, a new film by Danny Boyle in which an intrepid band of astronauts head off to save the Sun and mankind from an early grave.

Thankfully, it is all fiction. Astronomers are confident that the Sun is not going to peg out for another five or even six billion years. Go back just two hundred years though, and astronomers were almost totally in the dark.

The first glimmers of understanding

As the nineteenth century opened, William Herschel was famous thanks to his discovery of Uranus. He called for astronomy to be put to a bold new use. Instead of simply charting positions to aid navigation, he urged astronomers to investigate the workings of the Sun.

Herschel had realised that certain stars vary their brightness, and asked himself: what if the Sun were to vary in this way? A sudden dimming would be calamitous for agriculture. If astronomers could see the warning signs, provisions could be put in place and contingencies made. But what presaged solar variability? And how did a scientist deduce the Sun's composition? These were impenetrable questions. The fuel source that powered the Sun was a total mystery, and Herschel's rallying cry went unheeded.

In 1859, Robert Bunsen and Gustav Kirchhoff, working in Heidelberg, discovered the principle of spectral analysis. By passing sunlight through a prism, a pattern of dark lines is revealed. Each chemical element gives a different pattern. Bunsen and Kirchhoff realised how to decode these chemical 'fingerprints' and in doing so, gave astronomers a way to measure the composition of faraway celestial objects. Almost immediately, astronomers used the new technique to investigate the Sun. After much trial and error, they deduced that seventy five percent of the Sun is hydrogen, twenty three percent is helium, whilst the remaining two percent holds traces of all the other chemical elements.

The turning point for what powered the Sun was the discovery of nuclear fusion. Twentieth century astrophysicist Sir Arthur Eddington suggested that hydrogen fusing into helium caused the Sun to shine. By 1939, Subrahmanyan Chandrasekhar and Hans Bethe had independently calculated how the crushing force of gravity could liberate energy in a star by instigating nuclear fusion.

In fusion, two separate particles are forced so close together that they merge and become one. In this process, they give out energy. In the Sun, a constant sequence of mergers is building helium nuclei from hydrogen nuclei. The energy this liberates causes the Sun to shine.

But calculations to truly understand the workings of a star require computers. So the subject stalled until the 1950s, when computers developed during the Second World

War were used for civilian purposes. “That’s when science really took off. It was one of the first jobs that computers did after World War II,” says Simon Jeffery, Armagh Observatory.

As computing power advanced, so did the science. Astronomers discovered the Sun’s lifetime was billions of years, but a grim eventual fate awaited: the Sun would expand into a gigantic red star and probably swallow the Earth. Now, astronomers are predicting that, even before the red giant phase, the Sun has a nasty surprise for us.

Phase One: The hotter Sun

“The Sun gets around 10 percent hotter every billion years. That means long before the red giant stage, the Sun will make the Earth too hot for life,” says Don Brownlee from the University of Seattle, Washington. A hotter Sun will make current global warming look like a balmy summer’s day.

This is nothing new. The Sun has been steadily getting hotter since its birth 4.5 billion years ago. The reason is that, as it fuses hydrogen, the resultant helium accumulates in the core, like ash in a fire. As the helium builds up, the core becomes hotter and so the rate at which the remaining hydrogen fuses increases, releasing more energy and so the Sun’s surface gets hotter.

Just because the Sun will get inexorably hotter doesn’t mean we can do nothing. “Perhaps we can put sunshields in space to cut down the radiation getting to Earth,” suggests Brownlee. It is a fascinating concept pointing to space-based engineering on scales dwelling currently in the realms of science fiction. Sunshields would have to be kilometres in size to make any impact and there would need to be a fleet of them. Perhaps the sunshades will convert the blocked sunshine into electricity, via solar panels, and beam it to Earth to run the industrial air conditioning to further combat the rising temperatures.

Phase Two: The swallowed planets

Even if we can find a way to withstand the brightening of the Sun, things will worsen when the Sun’s stock of hydrogen finally runs out in its core.

A delicate balance of gravity and radiation holds the Sun together. Gravity tries to pull it together as the intense radiation produced by the nuclear fusion tries to blow it apart. As the fusion ceases in the core, the balance changes. Fusion moves into a shell around the inert helium core and drives the outer layers of the Sun to expand into a tenuous layer, up to a hundred times its present radius. “If you were standing in a room filled with red giant atmosphere, you would hardly notice it,” says Jeffery.

That’s because the average density of the gas is thousands of times less than water. Nevertheless, for the planets having to constantly orbit through this thin mist, the gradual accumulation of drag has profound implications. Their orbital energy will be gradually sapped over millions of years and they will spiral inwards to be consumed by the bloated star.

“Mercury’s fate is sealed,” says Pierre Maxted, an astrophysicist from Keele University. Venus’s, too, but the Earth may survive being swallowed – although the reason why means our planet is far from safe. As the Sun increases in size, so its brightness will also rise. “Eventually, the Sun will become 5000 times brighter than at present,” says Brownlee. Our planet, and even Mars will be charred to a crisp. The water-rich moons of Jupiter will be transformed into gigantic comets, their water billowing off into space for a million years or more.

Twice as far from the Sun as Jupiter, Saturn and its moon Titan may find the heat welcome. As ESA’s Huygens lander showed in 2004, Titan is a world scientists believe resembles the early Earth. An injection of heat may start the moon on a journey towards becoming a living place.

Titan will have to get its act together quickly; the red giant warmth will only last for about 0.5 billion years. Judging from the fossil record of the Earth, this is barely long enough for microbes to form. Of course, if there are any humans left in the Solar System at this stage, they may be grateful for Titan’s transformation, no matter how brief in astronomical terms.

But Titan is no safe haven. It could find itself cast adrift by the final act of the Sun’s death.

Phase Three: The scattering of planets

Red giants are unstable stars. At one point in the Sun’s red giant phase, it will revert to being a more normal, smaller yellow star. This is when the helium in its core ignites to fuse into carbon and oxygen. When the helium runs out, the Sun will again become a red giant. In this second red giant phase, pulses of nuclear activity power them. “The star becomes so luminous that it eventually blows itself to bits,” says Jeffery. This happens in a slow-motion explosion that sees the star push its outer layers off into space.

As the Sun sheds its outer layers, it loses mass. Consequently, the gravitational force generated by the Sun lessens. In effect, the Sun will loosen its grip on the remaining planets. At the very least, their orbits will grow larger; but it could all go pear-shaped. “The planet’s orbits could change chaotically,” says Maxted. If that were to happen, the orbits of the outer gas giant planets could become so distorted that they cross each other’s paths and their gravitational forces would throw one another around. This will result in some planets being thrown into the heart of the Sun, while others are cast out into deep space, to wander forever through the Galaxy. The moons of the outer planets would be torn from their parent worlds and either cast into the Sun or outer space.

So our planet will be burnt, swallowed or thrown away. Not exactly a rosy future but one that we can at least console ourselves won’t be happening in our lifetimes.

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The Sun – the story so far

Our Sun is often referred to as an average, middle-aged star. Most stars are actually smaller than the Sun, so by that measure it is a little bit special.

The higher the mass of a star, the faster it burns its stock of hydrogen fuel. In the case of the Sun, it will burn itself out in 10 billion years. Smaller stars, known as red dwarfs, persist for 100 billion years. At the other end of the scale, the most massive stars live just a few tens of millions of years.

Stars more than eight times the mass of the Sun suffer the most spectacular fates, blowing themselves to pieces in the form of supernovae. For a few weeks, this massive nuclear detonation makes them brighter than a hundred billion normal stars put together.

Sun stats

Mass:	1.989×10^{30} kg (332,946 Earths)
Diameter:	1,390,000 km (110 x Earth's)
Average density:	1.408 g/cm^3
Age:	4.6 billion years
Distance from centre of Galaxy: approx. 27,000 light-years	
Surface gravity:	273.95 m/s^2 (27.9 times stronger than Earth's)

The Sun is a naturally occurring nuclear fusion facility. It is predominantly made of hydrogen and helium. Most of this gas is not taking part in the nuclear reaction, but acts as the 'containment vessel' surrounding the nuclear reactor at the centre of the Sun.

The weight of the surrounding layers of gas compresses the core region, raising its temperature to around 15 million degrees centigrade. This is enough to ignite fusion between hydrogen atoms. As hydrogen fuses it releases energy, which takes hundreds of thousands of years to force its way to the surface of the Sun, where it escapes into space.

Ask the Expert
Dr Pierre Maxted, lecturer in astrophysics at Keele University

How complete is our understanding of stellar evolution?
We are certain about our models of stellar interiors for certain phases of a star's life. The main phase is when the star burns hydrogen in its core. For this phase we can make model predictions that agree to within one per cent of what we can observe on stars.

Where are we less certain?
We have trouble predicting the radii of low mass stars called red dwarfs. This is because the stars are relatively cool (astronomically speaking – they are still at 2000 degrees centigrade) and so have a lot of complex chemistry going on in their atmospheres. At the other end of the scale, the very massive stars are unstable and so

it is very difficult to make specific predictions about them, although we think we know the processes that take place.

What do you need to make progress?
We need observers to talk to theoreticians. That way, a theoretician can make a model prediction and an observer will realise that it can be tested using, say, a new instrument or telescope. Those observations will then provide new data for the theoretician to refine their model.

What mysteries remain about the Sun?
We almost understand the interior of the Sun more than the region of its atmosphere called the chromosphere. We know a lot about the interior because we have been observing sound waves ripple across the surface of the Sun for over twenty years. These sound waves travel down deep into the core of the Sun and bring information to the surface where we can observe them. The chromosphere is the region where solar storms take place, and we still do not understand them well.

Could the Sun take us by surprise and die tomorrow?
I can't think of a single physical mechanism that would do that. The Sun has been stable for the last four billion years and we observe many stable stars throughout the Universe. I'd say we are very confident that the Sun will remain stable for the next five to six billion years.

What's left behind?
Celestial butterfly
After everything else, what will remain of the Sun?

The Sun's final act will be to become a celestial butterfly. The layers of its outer atmosphere will drift ever further into space, creating a beautiful planetary nebula. They have nothing to do with planets but William Herschel, who discovered and named them, thought they resembled Uranus because both looked round and faintly green in his telescope.

A planetary nebula is composed of colourful veils of gas. They disperse a proportion of a star's chemical elements into space where they can be incorporated into the next generation of stars and planets.

The central core of the Sun will become a white dwarf: a stellar remnant so dense that, although it contains half the Sun's mass, it is no larger than the Earth. It should then fade away over the following ten billion years. However, it has one final chance for glory.

"The white dwarf's helium shell might just re-ignite," says Simon Jeffery of the Armagh Observatory. If this happens, the Sun will resurrect itself and in just a few years expand into a bright blue star. It won't last long; almost immediately it will get redder and cooler as it shrinks again.

Fly me to the Sun
Solar astronomers have never had it so good.

The more scientists recognise the connection between solar activity and electrical effects in Earth's vicinity, the more they want to study our central star – and there are plenty of missions already doing so.

The ESA/NASA solar watchdog SOHO (Solar and Heliospheric Observatory) has now been in space for 11 years. It was joined this year by a pair of NASA spacecraft called STEREO (Solar Terrestrial Relations Observatory) and the Japanese/UK/US mission Solar-B, recently renamed Hinode.

All these spacecraft are aimed at understanding more about the way in which the Sun releases storms of electrified particles that travel into the solar system and sometimes impact the Earth. Such solar storms can cause satellites to fail and disrupt communications and GSP signals on Earth.

The STEREO spacecraft is particularly interesting because it will return the first pseudo-three dimensional images of the Sun. Using its two spacecraft, it will watch the Sun from two different angles, allowing scientists to construct stereoscopic images of the Sun. In addition, SOHO will provide a third viewpoint, to help resolve any ambiguities in the data analysis.

The STEREO-SOHO data will allow, for the very first time, the three dimensional development of solar storms to be monitored, from their release at the solar surface to their impact with the Earth.

An instrument built in the UK on the Hinode spacecraft is targeting the ultraviolet variability of the Sun. This is currently thought to be of crucial importance in driving chemistry in the stratosphere of the Earth. Such high-altitude chemistry, and the resulting heat that is generated, can drive weather patterns such as the North Atlantic Oscillation, which affects the severity of European winters.

What's the effect on the Earth?	What's the science?	Did you know?
*Temperature The temperature of Earth is a direct result of the Sun's electromagnetic radiation. Most of this is light.	Light and infrared radiation are released into all directions of space by the solar surface. A minuscule fraction of this collides with the Earth. Clouds and ice sheets reflect some straight back into space but most is absorbed by the Earth. This absorption warms our planet. Carbon dioxide and other greenhouses gases trap a fraction of this heat in our atmosphere, making our planet warm enough for life. Current concerns about global warming rest on the increases in	William Herschel discovered infrared radiation whilst trying to develop an effective eyepiece for observing the Sun through a telescope. He found that green glass let through too much light but no heat, and that red glass

	these greenhouse gases, which causes more heat to be trapped in our atmosphere.	cut out enough light but let through heat. He correctly reasoned that light and heat are carried on different rays
*Weather The Earth's weather is powered by the solar energy stored in the atmosphere	There is a large debate about whether variations of the Sun can cause variations in the weather of the Earth. The light from the Sun varies by less than a tenth of one percent, but the ultraviolet radiation varies by a factor of one hundred. The Sun's magnetic activity is also extremely variable. Electrically charged particles from deep space, called cosmic rays, can be prevented from reaching the Earth when the Sun is magnetically active. There is growing evidence that cosmic rays influence cloud formation, and therefore Earth's weather. An experiment at one of CERN 's accelerators is currently attempting to understand the link between cosmic rays and clouds.	Between 1645 and 1715, the Sun lapsed into a period of deep magnetic calm when hardly a single sunspot was seen on its surface. This period of time coincides with the worst years of the so-called Little Ice Age, during which European winters were bitterly cold. The River Thames regularly froze and fairs were held on the ice. Coincidence or cause? No one is quite certain
*Aurorae The upper atmosphere of the Earth is sometimes driven to shine by electrified particles from the Sun striking our planet	Magnetically driven explosions on the Sun can fling giant clouds of electrically charged particles into space. These seething clouds contain billions of tonnes of solar gas and carry magnetic fields into space. The Earth itself is surrounded by a magnetic field that oscillates violently when a solar ejection strikes it. The solar particles burst into the upper atmosphere of the Earth and interact with nitrogen and oxygen atoms. In these violent interactions, the atoms begin to emit coloured light. The light can be green, red or violet but whenever it occurs, it speaks of our planet being assaulted by the Sun's magnetism.	The largest aurora in history took place on 2 September 1859. Two thirds of the planet were covered in blood red aurora, which even reached down into the northern tropics. Many from those regions had never even heard of aurorae. They though they were seeing an enormous fire. This aurora led to them being associated with solar storms.
Climate Ice ages may have their origins in the	The Earth is held to the Sun by gravity but this force still allows small variations to occur in the Earth's orbit.	If it were not for the Moon, the Earth's rotation axis would

variations that take place in the shape and size of the Earth's orbit around the Sun	Firstly, the shape of the Earth's orbit changes from circular to oval and back again every 100,000 years. Then, the tilt of the Earth's rotation axis dips from 22.1 to 24.5 degrees and back again every 40,000 years. Finally, the plane of the Earth's orbit tilts up and down a little every 70,000 years. The combination of these movements alters the strength of sunlight hitting the Earth and helps to cause the ice ages	be liable to tip over every hundred thousand years or so. This would drive our planet to more extreme changes in the climate. It could also mean that there were times when the Polar Regions were hotter than the equator, because our planet had tipped right over