Touching the Sun

Professor Chris Lintott, Gresham Professor of Astronomy

15 January 2025

The Sun is the most familiar celestial object, but it remains a mystery to us, and hence an object of both fascination and scientific investigation. Last Christmas Eve, the Parker Solar Probe whizzed just 3.8 million miles above the visible surface of our star, moving at 430,000 mph – a speed that makes it the fastest human made object ever. In doing so, it fulfilled an ambition which dates back to at least the founding years of the space age, and bettered Icarus, surviving temperatures of nearly 1000 degrees centigrade. Thanks to a state of the art heat shield, its instruments were kept at nearly room temperature, allowing them to probe and understand this exotic environment.

You can follow the Parker Solar Probe at https://science.nasa.gov/mission/parker-solar-probe/

Parker's epic voyage is part of a coordinated program to observe our nearest star; most notably, it is joined in the fleet by the European Space Agency's Solar Orbiter (https://www.esa.int/Science_Exploration/Space_Science/Solar_Orbiter). Solar Orbiter is ten times further away, but has cameras and sophisticated instruments which give a view of what our dynamic and changing star is up to. As well as a fleet of observatories in orbits around and near the Earth, the two Voyager probes, launched to explore the outer planets, are acting as solar observatories at or even beyond the edge of the Solar System (https://science.nasa.gov/mission/voyager/interstellar-mission/); the present epoch is likely the only period in our lifetimes when we will observe the Sun from close up and far away.

Fred Hoyle once started a lecture in Cambridge by noting 'Stars are simple'. A heckler from the back shouted 'If you were that far away, you'd look simple too, Fred'. The Sun is the only star that is close enough that we can see how complex it is.

When I started writing this lecture I was in the midst of pre-Christmas burnout. After about an hour I had a page that just said 'Sun – hot' on it. But this is fundamentally what was known about the Sun – but the source of its heat was controversial.

Initially, the controversy was whether the Sun was hot at all. The great observer William Herschel, who thought he had seen structure on the surface of the Sun, assumed that it must be a planet like any other, a cold place inhabited by intelligent beings. (He reasoned that just because the Sun was a source of heat it didn't need to be hot itself, he did point out that its conditions might be a suitable place for the punishment of the wicked).

There's a good essay from John Bachall on how we found out how the Sun produced its energy here: https://www.nobelprize.org/prizes/themes/how-the-sun-shines/

In the nineteenth century, ideas about producing energy through necessarily slow gravitational contraction, or via the bombarding of the Sun with a ceaseless rain of comets and asteroids, were common. However, new geological understanding of the age of the Earth made it clear that our planet, and hence the Sun, must have existed for hundreds of millions, if not billions of years, so none of these methods would do. The discovery of radioactivity suggested an alternative possibility, but spectral observations had shown that the Sun was devoid of radioactive elements, being composed mostly of hydrogen.

Eddington in 1926 was able to write that ‘At first sight it would seem that the deep interior of the sun and stars is less accessible than any other region of the universe’, but by 1920 astronomers had worked out both that the enormous temperatures, reaching to tens of millions of degrees, achieved at the centre of the Sun, made nuclear reactions possible.

We can consider nuclei, incidentally, because those same high temperatures mean that the Sun is essentially a ball of plasma, with electrons liberated from their atomic nuclei[1].

At the temperature of the centre of the Sun, when protons (hydrogen nuclei, stripped of their electrons) collide, just occasionally they combine to form a heavier nucleus. A chain of similar reactions, known as the proton-proton cycle, ensues, eventually converting four hydrogen nuclei to a single nucleus of helium. Though both the beginning and end state contains four nucleons (protons and neutrons), the product – helium – has a slightly lower mass than the input. As Einstein taught us E= mc^2, and the resulting loss of a small amount of mass corresponds to a significant release of energy. Every second, the Sun loses four million tonnes of matter.

The other by-product of the proton-proton cycle are subatomic particles called neutrinos, which escape the Sun’s core and flow into the surrounding space. These particles are elusive (John Updike wrote a poem called ‘Cosmic Gall’ which notes that they ‘hardly interact at all’[2] but starting in the 1960s they could be detected by a suite of ingenious particle physics experiments (see https://warwick.ac.uk/fac/sci/physics/staff/academic/boyd/stuff/neutrinolectures/lec_neutrinodetectors_writeup.pdf for details). Despite a long-lived ‘solar neutrino problem’, in which the flux of neutrinos detected at Earth seemed to be much less than expected, eventually resolved by a better understanding of the physics of neutrino behaviour, these results provided direct evidence for the predicted proton-proton cycle.

Neutrinos can escape from the Sun easily. The same is not true for photons, which in the dense conditions of the Sun’s core and inner layers are often absorbed and reemitted. On average, it takes a photon approximately 170,000 years to escape from the Sun’s core; we’re seeing light now which is the product of reactions which occurred not long after homo sapiens left Africa.

Thanks in part to helioseismology, the study of sunquakes and of the pulsing and rippling of the star, we know something of the Sun’s inner structure. (see https://gong.nso.edu/info/helioseismology.html for am introduction to helioseismology) A still mysterious core, home to the nuclear reactions, is surrounded by a radiative zone, where energy transfer is mostly via the movement of photons, which is in turn topped by a convective zone, where heat is transferred by the movement of plasma in large cells, reminiscent of the circulation of air in the Earth’s atmosphere.

This activity might lead one to expect a chaotic boundary between the Sun and the rest of the solar system.

---

[1] The band ‘They Might Be Giants’ had a minor hit with ‘Why does the Sun shine?’, a song which proclaimed that ‘The Sun is a Mass of Incadescent Gas’. They have corrected their mistake with an updated version: ‘The Sun is a Miasma of Incadescent Plasma’ https://open.spotify.com/track/16HQ0SsRblCVsu1OJiMy9R?si=81afe513a61a4f10

[2] And indeed, that they penetrate you and me. He calls it crass, noting that 10^11 neutrinos pass through each square centimetre of your body every second.

Yet seen from Earth the Sun seems to have a distinct surface, albeit one that with sufficiently high resolution images seems to bubble and boil (The surface is seen to be split into small cells, known as granules). This is the photosphere, a region only 500 km thick, in which the density of the plasma drops to a level just 10,000th of that of the air at sea level on Earth, and photons can finally travel freely out into space.

This, then is the light that we get from the Sun, at least in the visible region of the spectrum. That light was intensively studied by a group of 19th century physicists, including the founder of *Nature*, the entrepreneurial Norman Lockyer, who found that it was marked by a series of dark spectral lines at particular wavelengths. Many of these ‘Fraunhofer lines’ were associated with known elements, but one sequence did not match anything in the laboratory – lines associated with helium, found on the Sun long before being identified Earth.

The Fraunhofer lines are dark against a bright background. The bright background itself comes from emission from an unusual state of matter – negative hydrogen atoms. In the rarefied conditions of the Sun’s upper atmosphere, protons can form weak bonds with a second electron; though this is rare, with only one in 10^8 hydrogen atoms in this state, emission associated with the loss of this second electron provides the continuous rainbow onto which the Sun’s absorption spectrum is imposed.

When the first astronomers used telescopes to look at the Sun[3] (notably British astronomer Thomas Harriot, whose 1610 observations may have predated Galileo’s) they found a disk marred by sunspots, small dark regions that come and go across the face of the star’s disk. (Galileo’s detailed observations are available here: http://galileo.rice.edu/sci/observations/sunspots.html) Observations made at the same time each day reveal the rotation of the Sun, which – as the Sun is not solid – varies with latitude, from 24.5 days near the equator to 36 days near the poles. The sunspots themselves are depressions in the plasma (a fact revealed by a study of their shapes) of the photosphere, cooler regions where light can escape from deeper in the Sun’s structure.

Spots are the most obvious result of the complex magnetic fields which shape the Sun’s structure. (Astronomer Robert Leighton noted in 1965 that ‘*If the Sun had no magnetic field, it would be as uninteresting as most astronomers think it is’*). Though it is likely that the primordial magnetic field associated with the Sun took the simple form we see at the Earth, the differential rotation mentioned above twists it, with the complex interactions of magnetic field and charged plasma meaning that a twist around the Sun is completed every eight months. What starts as a simple field becomes complex, storing energy and leading to the solar activity we see today, imposing a wide range of dynamic behaviour on our simple Sun.

It became obvious, for example, that the sunspots follow a roughly 11 year cycle of activity, with the first examples of each cycle appearing at high latitudes before moving down towards the equator. (This pattern produces the so-called butterfly diagram, which can be seen here: https://www2.hao.ucar.edu/education/pictorial/butterfly-diagram) We are currently near the maximum of cycle 25, counted up from 1755 when systematic sunspot observation began[4]. Studies from spacecraft of the Sun’s magnetic field revealed that sunspots come in pairs, of opposite polarity, with alternate cycles producing pairs led by first one pole, then the other.

---

[3] Do not look directly at the Sun – it is dangerous, and can cause permanent eye damage. The best way to view the Sun is by projecting its image.

[4] One can measure one’s life in sunspot cycles; I was born in cycle 21, which was reasonably dramatic, went to school during quieter cycle 22, was at university during the surprisingly calm cycle 23 and moved to America for the very quiet cycle 24. If this suggests a long-term trend to less activity, for the Sun if not myself, then you may be onto something – longer-term cycles imposed on the most obvious 11 year one may suggest we are heading for a lull in solar activity which matches that experienced in the 16th century.

These observations eventually led to a picture where sunspots are places where the twisted magnetic field interacts with the photosphere. As the leading spot is always closer the poles, as the magnetic field associated with the sunspot moves up in latitude, the polar field is weakened, leading to the eventually flipping of the poles between cycles.

Sunspots are signs that the sun's dynamo is transferring magnetic flux into its outer atmosphere. The effect of this is best seen during a total solar eclipse, when the Moon blocks the bright photosphere and the Sun's outer atmosphere, the corona, is revealed. (The definitive guide to viewing solar eclipses, an experience I highly recommend, is https://www.eclipsewise.com/). Total eclipses are rare, with more than one a year across the whole Earth seldom seen, and the pearly-white corona changes shape between totalities; a solar maximum corona tends to be symmetrical, whereas a dipole – with long streamers – is more common at solar minimum.

Though eclipses are necessary to get a glimpse of the corona, astronomers have learnt to use wavelengths beyond the visible to study the Sun. A switch to x-rays, with observations initially carried out by telescopes swinging under high-altitude balloons, carried on sounding rockets and, during one glorious run of experiments, on a rockoon (a rocket launched from a balloon), reveals that the corona is hot, much hotter than the photosphere underneath it.

This feels like a paradox, though it is worth remembering that the corona is extremely low density and so the total amount of energy being transferred is small. Missions such as TRACE (https://www.cfa.harvard.edu/facilities-technology/telescopes-instruments/transition-region-and-coronal-explorer-trace) studied coronal loops, massive transient structures which reach up into the corona, and which seem to play an important role in heating it; full confirmation of exactly what is happening in this transition region will need to wait for further passages and analysis of the Parker Solar Probe.

We on Earth exist within the Sun's atmosphere. A steady wind of particles flows from the Sun out through the solar system, and missions such as STEREO, which consists of two spacecraft strung out along Earth's orbit with one leading and one following the planet, have monitored conditions within this wind. (see https://www.ralspace.stfc.ac.uk/Pages/STEREO.aspx). Important early results from Solar Orbiter have located the sources of the fast and slow components of this solar wind, linking what's seen at the spacecraft with activity on the surface of the Sun. The next challenge is understanding how the particles in the solar wind are accelerated, a process known to occur close to the Sun's surface; it is Parker's ability to fly through the region before the wind becomes supersonic that most excites solar scientists, who feel that they are visiting a new regime.

The Earth's magnetic fields protects us from the worst effects of the solar wind, though the occasional display of northern or southern aurorae can act as a reminder of the Sun's power. More powerful events, from the solar flares associated with sunspot groups to powerful coronal mass ejections, capable of throwing a billion tonnes of matter away from the Sun at a million miles an hour, can have more dramatic effects. The story of Richard Carrington, who in 1859 spotted a dramatic explosion on the surface of the Sun and associated it with spectacular aurorae and electrical storms strong enough to interfere with electrical systems (the famous example is that telegraph operators found their boards sparking even when disconnected from power) that occurred a few hours later is brilliantly told in Stuart Clark's 'The Sun Kings' (Princeton, 2009). An especially dramatic CME can be seen in progress in drawings of the 1860 total eclipse, during what was clearly a very active solar maximum.

Recent results from Jenny O'Kane at UCL's Mullard Space Science Laboratory in Dorking used Solar Orbiter results to identify the source of a 'stealth' CME, one detected by particles crossing the spacecraft and which seems to have come from a quiet region of the Sun; though this is low energy by CME standards, it retains strong magnetic fields, and such events may be responsible for driving stormy space weather on Earth even though they are hard to see. Understanding space weather will require a new fleet of monitoring satellites to keep track of everything the Sun can throw at us.

Beyond the Earth, the solar wind continues to spread out into the Solar System. Eventually, out beyond Neptune, there is a region called the heliopause where the pressure of the solar wind matches that of the interstellar medium. The two Voyager probes have encountered this transition region, and showed that the boundary between our solar system and the rest of the galaxy seems to have a complex structure, built up through the bubbles produced by flare after flare and CME after CME. The twisting and broiling of the hot plasma and its entangled magnetic fields leaves an imprint, even out on the edge of the Solar System.

Beyond that, our Sun is just one star amongst many. Somewhere amongst its hundred billion or so neighbours in the Milky Way will be a handful of siblings, stars born at the same time and in the same place as our own. Finding them will help us understand whether the Sun is unusual – or whether, in all its complexity, it is a typical star. Leading this effort is ESA's great celestial cartographer, Gaia, which ceased observing after a more than decade long effort to map more than a billion stars – and we'll be looking at what it has told us in the next lecture of this series.

Further Reading and Resources

The best general introduction to the Sun and its physics is '15 million degrees' by Lucie Green, (Penguin, 2016). I drew on it heavily in preparing this lecture.

The Solar Dynamics Observatory provides up to date images of our Sun and its activity: https://sdo.gsfc.nasa.gov/data/

A new generation of telescopes are getting ready to study the Sun from the ground: see https://est-east.eu/ and https://nso.edu/telescopes/inouye-solar-telescope/ for details of these astonishing instruments.

In the UK space weather forecasts are provided by the Met Office: https://www.metoffice.gov.uk/weather/specialist-forecasts/space-weather and more specific forecasts of UK aurora activity are maintained by AuroraWatch: https://aurorawatch.l