Oxford Cambridge and RSA

Friday 10 June 2022 – Afternoon

A Level Physics B (Advancing Physics)

H557/02 Scientific literacy in physics

Advance Notice Article

Time allowed: 2 hours 15 minutes

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The new Icarus?

In the Greek myth of Daedalus and Icarus, Daedalus makes sets of wings out of feathers and wax for himself and his son so that they can fly to escape their captors. Icarus ignores his father's advice to keep near the ground and flies as high as he can. The heat from the Sun melts the wax holding his wings together and the young man plummets to his death. The myth gives us a warning against over confidence – 'don't fly too close to the Sun'. But, for physicists and astronomers, one way to learn more about our nearest star is to fly as close to it as possible, but using more suitable materials than feathers and wax.

The Sun emits electromagnetic radiation. It has produced a near-constant radiant power of 4×10^{26} W for around 5 billion years and is only around half-way through its supply of hydrogen fuel. At the Earth, the radiant power from the Sun is uniformly spread over the surface of a sphere of radius 1.5×10^{11} m – the Earth-Sun distance. So, the power received from the Sun becomes a life-supporting intensity of 1400 W m^{-2}.

Civilisations throughout history have recognised the supreme importance of the Sun to life on Earth and it has been known for many years that the Sun drives the weather. In more recent times, other observations have been linked to the Sun, including the spectacular aurorae – the Northern and Southern Lights that sometimes hang like shimmering, shifting curtains of coloured light across the night sky at high latitudes. An image of such a display is shown in **Fig. 1**, but photographs scarcely capture the spectacle.

Fig. 1 The aurora borealis or Northern Lights seen from Tromsø in Norway.

These wonderful phenomena are caused by the solar wind, a hail of charged particles (mostly protons and electrons) travelling at around 500 km s^{-1}. These charged particles spiral down the magnetic field near the poles. This is because the component of their velocity perpendicular to the Earth's magnetic field makes the charged particles orbit the field lines while the velocity component parallel to the field is unaffected. The charged particles transfer energy to electrons in atoms in the atmosphere producing the spectacular lighting effects. These and other examples of 'space weather' can be very dramatic, damaging satellites, navigation systems and electrical transmission lines amongst much else. Space weather has become such an important topic that space probes have been sent tantalisingly close to the Sun to investigate its causes and you can even get a space weather forecast from the Met Office. To consider how the Sun pushes out this stream of charged particles we must first think about the ultimate source of the Sun's energy – the fusion of hydrogen in its core.

The proton-proton cycle

Hydrogen is fused into helium in the Sun's core (see **Fig. 2**) in a three-stage process:

$${}^{1}_{1}\text{H} + {}^{1}_{1}\text{H} \rightarrow {}^{2}_{1}\text{H} + {}^{0}_{+1}\text{e} + {}^{0}_{0}\nu$$

$${}^{2}_{1}\text{H} + {}^{1}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + \gamma$$

$${}^{3}_{2}\text{He} + {}^{3}_{2}\text{He} \rightarrow {}^{4}_{2}\text{He} + 2\,{}^{1}_{1}\text{H}$$

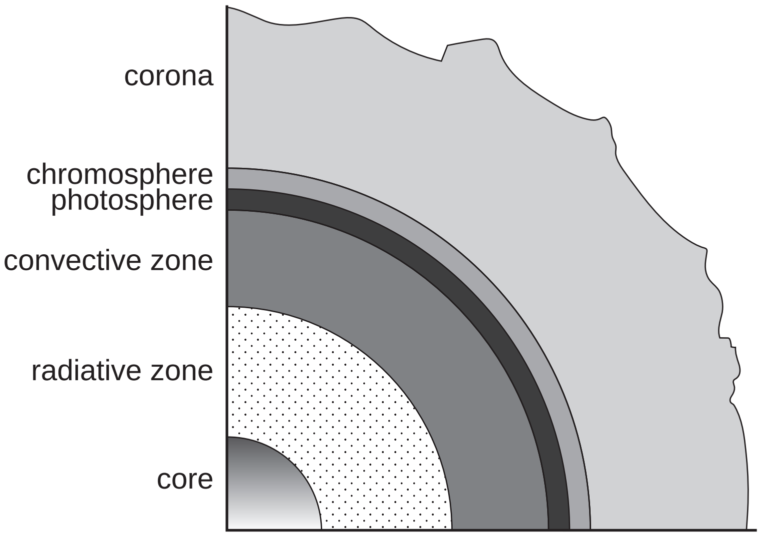

Fig. 2 Cross-section of Sun, not to scale.

Fusion requires extremely high temperatures to give the protons sufficient energy to overcome electrostatic (Coulomb) repulsion. But even at the temperature of the core, the average energy of the protons is not enough to allow fusion. Of course, some protons will have energies far greater than the average but they still fall short of the energy needed for fusion. This provided a puzzle for physicists which was finally explained by a process known as quantum tunnelling. The low probability associated with these reactions means that the Sun is working through its fuel at a slow and stable rate. This is important, if fusion reactions were more likely, and therefore more frequent, the fuel would be used more quickly and life on Earth would not have time to evolve.

The structure of the Sun

About 98% of the energy of the fusion reaction is taken away by gamma ray photons, the remaining energy carried away by the neutrinos produced in the first stage of the process. The neutrinos reach the Earth in less than ten minutes whereas it takes the electromagnetic radiation about 100 000 years to make its way through the so-called radiative zone of the Sun, a region of ions and free electrons called a plasma. During their journey through the radiative zone, the gamma ray photons are absorbed and re-radiated by electrons in the plasma or ionised fluid that makes up much of the Sun. This absorption and re-radiation changes the direction (and energy) of the photons. Each photon's path, a 'random walk,' is described by the equation

$$d = x\sqrt{n}$$

where d is the displacement of the photon from its starting point after n steps of length x. So the total distance the photons travel is much greater than their displacement.

As the name suggests, the region above the radiative zone transfers energy up to the surface by process of convection. The movement of charged particles throughout this region gives rise to the Sun's complex and changing magnetic field. Above the convection zone the pressure and density reduce, allowing photons to travel far greater distances before interacting with particles. This is the photosphere, the 'surface' of the Sun we see in visible light photographs. The colour of the Sun gives a clue to the temperature of the photosphere. The Sun radiates in all regions of the electromagnetic spectrum but gives out most visible light in the yellow region. From this we can make an estimate of the temperature of the photosphere using the relationship derived by the German physicist Wilhelm Wien in 1893:

$$\lambda_{max} \propto \frac{1}{T}$$

This states that the peak wavelength λ_{max} of the emitted electromagnetic radiation is inversely proportional to the kelvin temperature T of the object. This tells us, for instance, that the temperature of an electric toaster element glowing red hot is the same as the surface of a red giant star.

The chromosphere, lying above the photosphere, can be observed during total solar eclipses as a red region around the hidden Sun – the red colour coming from electrons moving between two specific energy levels in hydrogen.

The solar wind emerges from the corona, the outer region of the Sun (see **Fig. 3**). This is a very low-pressure region which emits changing patterns of electromagnetic radiation that show the structure of the magnetic field guiding the movement of the particles that make up the corona. The temperature of the corona can reach above 2 million K. This gives the particles sufficient energy to emit X-ray emissions that can be observed by spacecraft. One of the unresolved questions of solar physics is how the corona can be hotter than the lower layers which are closer to the energy-producing core.

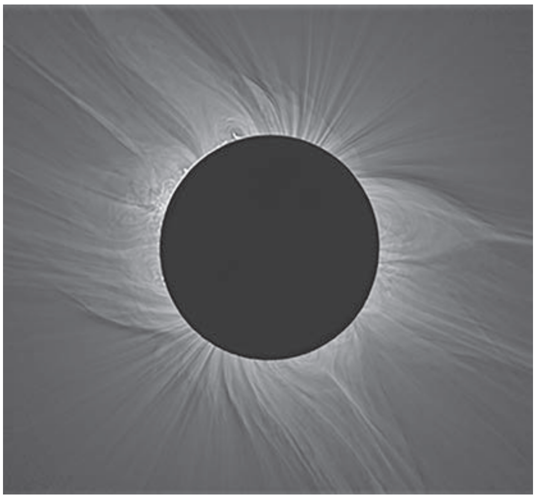

Fig. 3 The solar corona – the corona makes a pattern similar to that of a bar magnet with poles at roughly 1 o'clock and 7 o'clock.

The Carrington Event

On 1st September 1859 the British amateur astronomer Richard Carrington observed extremely bright streamers of light around a group of sunspots, dark regions on the face of the Sun. This observation, independently noted by another astronomer, Richard Hodgson, was the first recording of a solar flare. These events are often associated with 'coronal mass ejections' or CMEs which, as the name suggests, eject matter from the corona into space. Solar flares are associated with rapid releases of plasma and ions with a typical total energy of 10^{20} to

10^{25} J. The material travels through space at relativistic speeds and carries its own magnetic field which can distort and temporarily reduce the Earth's protective magnetic field when the speeding particles approach the Earth.

On 2nd September 1859, just 18 hours after Carrington observed the flares, telegraph operators on both sides of the globe reported getting electric shocks and in at least one case disconnected their electrical apparatus from the supply and continued to use it with the currents induced in the wire by the magnetic field associated with the solar flares. **Fig. 4** shows a recent solar flare.

Fig. 4 A very large solar flare observed in 2017.

The Earth's magnetic field deflects much of the solar wind as shown in **Fig. 5**. As can be seen, some of the solar wind passes down towards the poles, this is the cause of the aurora.

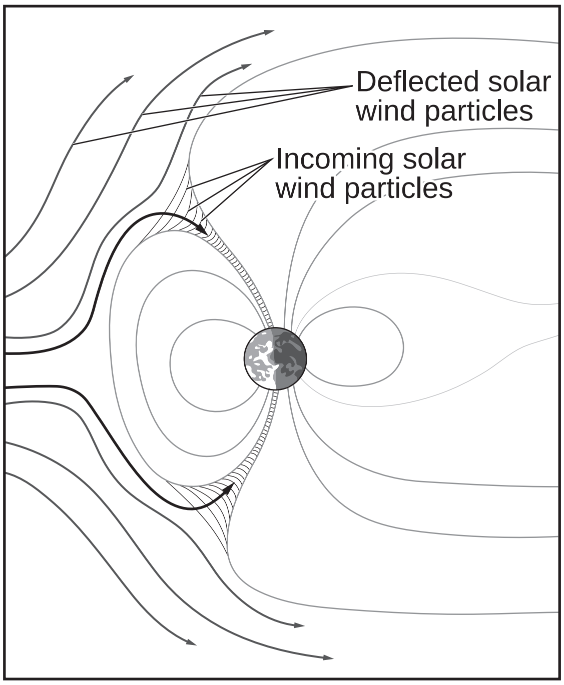

Fig. 5 The Earth's magnetic field deflecting much of the solar wind – this protection is temporarily reduced when a CME approaches the Earth.

Back in 1859, there was little sensitive or large-scale electrical equipment that could be damaged by such 'geomagnetic storms' as the Carrington Event. Things were different in March 1989 when another coronal mass ejection cut out the power to millions of people in Canada for several hours. In the modern world of cross-globe communication a geomagnetic storm of the magnitude of the Carrington Event would cause great disturbance to the lives of many millions of people and have significant economic impact. These are both reasons why solar research is such an important field.

One of the most ambitious research missions is the Parker Solar Probe, launched in 2018. The probe is designed to perform a series of passes over the Sun in a gradually changing orbit. In January 2021 it passed within about 14 billion metres of the Sun, about a quarter of the distance that Mercury orbits. At its closest approach the speed of the probe was 130 $km\,s^{-1}$ – at this speed it would take just 50 minutes to travel from the Earth to the Moon.

The power from the Sun at such a small distance is very great and would be expected to raise the temperature of the probe to extremely high temperatures. We can get an idea of the temperature it may reach if we make the simplifying assumption that the probe is in thermal equilibrium – that it radiates as much power per square metre as it absorbs. If this is the case the probe would be behaving as a 'black-body radiator' and we can use Stefan's Law to estimate the temperature. This states:

Power absorbed or emitted per unit area in thermal equilibrium = σT^4

where T is the kelvin temperature and σ is Stefan's constant = $5.7 \times 10^{-8}\,W\,m^{-2}\,K^{-4}$.

The probe has a large heat shield, as shown in **Fig. 6**, which always faces the Sun. More precise calculations show that the shield will reach temperatures of around 1350 °C whilst the instruments behind it remain at about 30 °C. The instruments will measure the magnetic and electric fields of the corona and help scientists understand the nature of the Sun and the cause of the flares and coronal mass ejections.

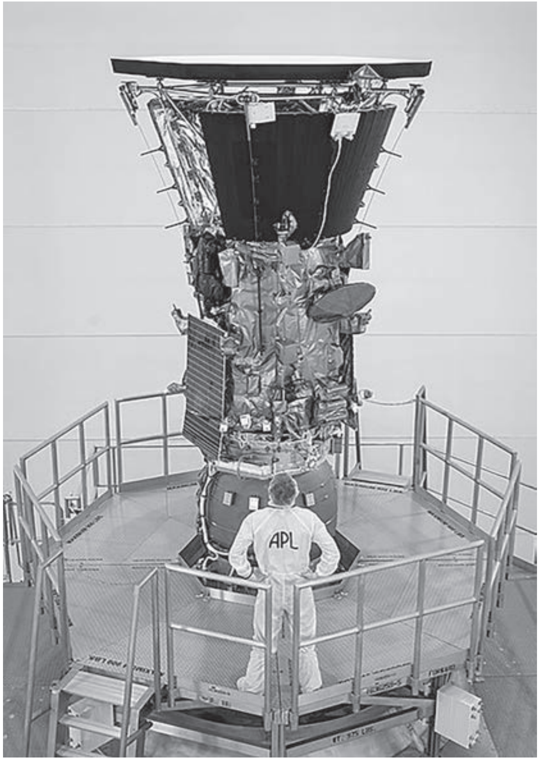

Fig. 6 The Parker solar probe. The heat shield is the flat, white-topped sheet on the top of the probe.

The probe gets far closer to the Sun than the mythical Icarus and has already sent back valuable information to help scientists understand our nearest star. With greater knowledge of the physics of the Sun we may be able to predict when the Earth is likely to experience a severe bout of 'space weather' and take precautions to protect our electromagnetically-dependent society.

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