OXFORD CAMBRIDGE AND RSA EXAMINATIONS

Advanced GCE

PHYSICS B (ADVANCING PHYSICS) 2865/01

Advances in Physics

INSERT

Thursday **22 JUNE 2006** Afternoon 1 hour 30 minutes

INSTRUCTIONS TO CANDIDATES

- This insert contains the article required to answer the questions in Section A.

This insert consists of 8 printed pages.

The Variable Sun

Observing the Sun

Since the earliest times, people have made detailed observations of the Sun, noted how the path of the Sun across the sky varied with the seasons and used this to define the year. With the invention of the telescope, closer observation became possible. The presence of sunspots, discovered by Galileo at the time when the sun-centred model of the Solar System was becoming established, signalled a change in our attitude to the Sun. It ceased to be thought of as a perfect, heavenly body and became instead a mysterious, complex object to be studied in its own right.

Once it was accepted that the Sun and all members of the Solar System should obey the laws of physics, there were questions to be answered. Where does the Sun get its energy? What causes the strange black sunspots which disfigure its surface? And why are there patterns in the movement and number of sunspots which vary with time? In tackling these questions, significant discoveries in fundamental physics have been made.

The source of the Sun's energy

Thermodynamics developed as a science in the nineteenth century, and it became clear that chemical reactions, such as in a coal fire, could not provide enough energy for the Sun to last more than a few thousand years. Geological evidence at this time suggested that the Earth must be many millions of years old, so another energy source had to be found. The German scientist Helmholtz suggested that gravity could supply the energy as meteors fell into the Sun. However, the mass of meteors needed to provide the 4×10^{26} W that the Sun emits is huge, of the order of 10^{15} kg each second. It seems unlikely that matter is falling into the Sun at a rate equal to the mass of the Moon every year or two.

In 1887 Lord Kelvin developed this idea further, and suggested that the Sun began as a huge cloud of gas and dust which began shrinking due to the gravitational attractions between its particles. As the cloud collapsed it got continually hotter. Once reaching the size of the present-day Sun, the core temperature would be millions of degrees, and the pressure of the very hot interior would prevent any further collapse. Under these conditions, the star would take a long time to cool, and once it did, the in-falling matter of the resulting contraction would once again produce heat. Kelvin calculated that the Sun's radius had to shrink only about 50 cm per year to keep the Sun's output fairly steady for tens of millions of years. Geologists still felt that this time was not long enough to agree with the age of the rocks on Earth, but no better explanation could be found at that time.

The discovery and study of radioactivity in the first half of the 20th century provided an explanation. Radioactive decay releases large amounts of energy, so it was suggested as a source of the Sun's power. It was eventually realised that nuclear fusion provided the solution. The gravitational collapse that Lord Kelvin had suggested half a century earlier produces extremely high temperatures and pressures. In fact, the temperatures inside stars are so high that atoms are stripped of all their electrons, producing a plasma of positive and negative ions. At these extremes of temperature and pressure, nuclei in this plasma can fuse, releasing energy.

In a small star like our Sun, energy is mostly produced by a series of three nuclear reactions called the proton-proton chain. In this process, protons first combine to form deuterons (hydrogen-2 nuclei). This process is extremely infrequent, happening to a pair of colliding protons only once in about 10^{10} years. The deuterons quickly (within about a second) react with further protons to give helium-3 nuclei. Finally, in another process, on a time scale of about a million years, pairs of these helium-3 nuclei combine to give ordinary helium-4 nuclei. The net result of this series of processes is to combine four protons to form a helium-4 nucleus, with the emission of two positrons, two neutrinos and gamma photons, as shown in Fig. 1.

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Details: A diagram showing the combination of four protons to form a helium-4 nucleus

Fig. 1

The energy liberated in this process is over 24MeV. The two positrons produced in stage 2 annihilate with two electrons in the Sun's core to produce another 2MeV, so that over 26MeV is produced for every four protons converted into helium nuclei. The Sun's core contains about 6×10^{29} kg of hydrogen, and this would allow the production of energy at the current rate of 4×10^{26} W for several billion years. This agrees well with geological estimates of the Earth's age, and confirms the proton-proton chain as a reasonable model of power production in the Sun.

Sunspots

Sunspots are darker regions in the Sun's surface. These are places that are significantly cooler than the 5800K of the surrounding regions; as low as 4000K for a big sunspot. Sunspots appear dark compared with the surrounding photosphere, even though a large sunspot is still radiating about 20% of the energy of a surrounding region of the same size. If it were not for the surrounding photosphere, each sunspot would look very bright.

Regular systematic observations of sunspots followed Galileo's first observations in 1610, and it was noted that the number of sunspots fluctuated with a pattern of mean period eleven years (Fig. 2).

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Details: A graph of the Yearly Averaged Sunspot Numbers from 1610-2000

Fig. 2

The almost complete lack of sunspot activity between 1650 and 1700, known as the Maunder Minimum, coincided with a time of intense cold in Europe and North America. There is no agreement that these two occurrences are linked, but it has been suggested that the absence of sunspots coincided with the Sun rotating more slowly, and also becoming slightly larger and cooler.

[Turn over

More recent observation of sunspots has shown that they have huge magnetic fields, about 0.1T, which are two orders of magnitude larger than in the surrounding regions of the Sun, and three orders of magnitude higher than the Earth's magnetic field. The Sun's magnetic field has been observed to reverse every eleven years, which suggests that it is linked with the sunspot cycle. One theory of the Sun's magnetism suggests that the turbulent plasma within the Sun causes the magnetic field to kink, and sometimes loop out of the Sun's surface. Sunspots occur wherever the field enters or leaves the Sun's surface. Every eleven years the Sun's magnetic field flips over. It did this last at the end of the year 2000, so the next reverse is expected at the end of 2011, at the next time of maximum sunspot activity.

SOHO

Although ground-based observations have given much information about the Sun for many centuries and will continue to do so, there are clear advantages to observing from space, avoiding atmospheric interference and using frequencies not transmitted through our atmosphere. The Solar and Heliospheric Observatory (SOHO) was set up in 1995 by the European Space Agency and NASA to study the Sun from space. SOHO gave so much information about the structure and behaviour of the Sun that its initial two year mission was extended to twelve years, allowing it to study the Sun during an entire sunspot cycle.

Most space observatories orbit the Earth, moving in and out of the Earth's shadow as they do so. But SOHO was placed in solar orbit between the Earth and the Sun, so that it would have an uninterrupted view of the Sun (Fig. 3).

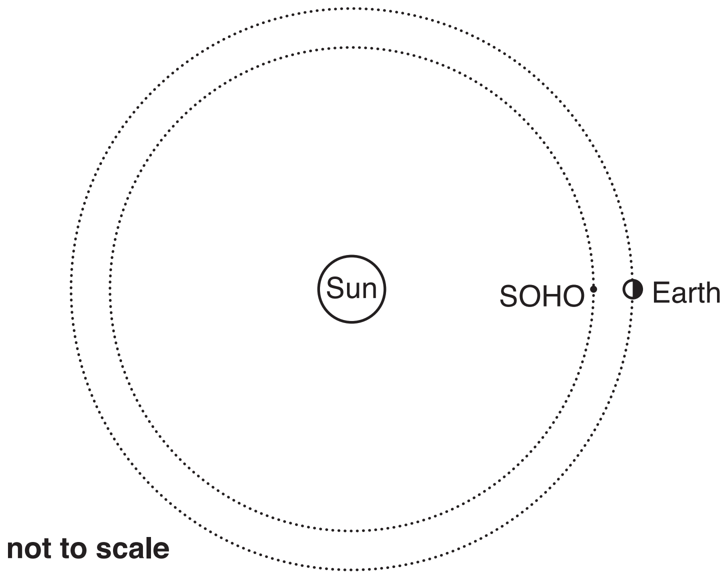

Fig. 3

Because SOHO has a smaller orbital radius than the Earth, you would expect it to orbit the Sun in a shorter period than the Earth. However, SOHO is acted on by the gravitational fields of both the Sun and the Earth. This problem has been known since the time of Newton as the *three-body problem*, where an object is acted upon gravitationally by two others. Although there is no complete solution for this problem, the French mathematician Joseph-Louis Lagrange found some special places where the smallest body of the three could keep the same position relative to the other two, and SOHO is placed at one of these. In this case, the resultant centripetal force on SOHO is slightly smaller than would be expected if the Sun alone were acting on it, due to the attraction of the Earth. As a consequence of this reduced inward force, the orbital periodic time is slightly longer. At SOHO's position, about 1% of the way from Earth to the Sun, the period is exactly one year, so it remains along the straight line joining the Earth to the Sun.

Comets, Solar Wind and the Corona

Long-tailed comets, appearing unpredictably in the night sky, were even more mysterious to the ancients than the wandering planets. People were not sure whether comets were atmospheric or heavenly phenomena. Edmund Halley was the first to apply Newton's Laws to predict the return of the comet now named after him. Since that time comets have been recognised as members of the Solar System with orbits that are often extremely elliptical.

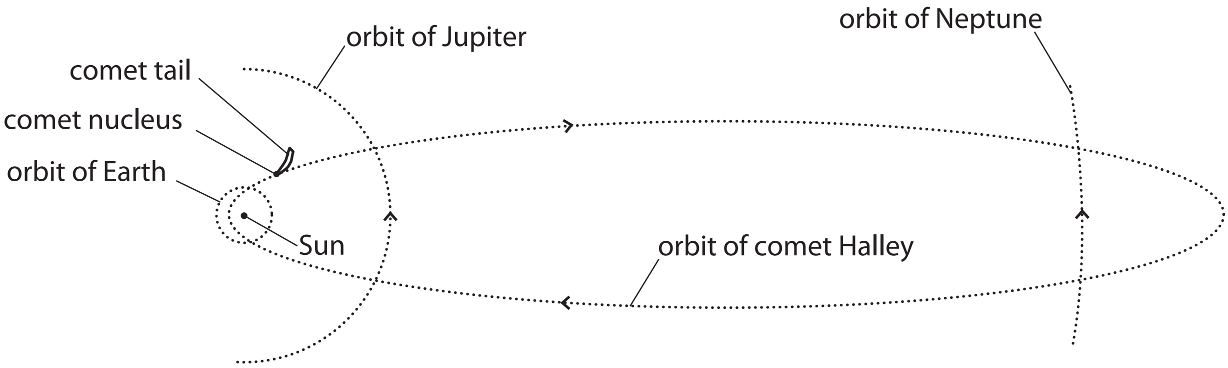

Fig. 4

The comet's tail appears only when it is close to the Sun, suggesting that it is produced as the nucleus of the comet heats up. Chinese astronomers about 2500 years ago observed that the tail of a comet invariably points away from the Sun. This can only be explained as the result of pressure due to some substance being emitted by the Sun. The existence of this 'solar wind' was confirmed in 1959 by the Soviet Luna 3 spacecraft.

Comets often have two separate tails. Comet Hale-Bopp, which was at its brightest during March and April 1997, clearly showed these twin tails (Fig. 5).

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Details: An image of the comet Hale-Bopp showing twin tails

Fig. 5

One tail consists of dust particles, and often shows a slight bend, as seen in Fig. 4 and the upper tail of Fig. 5. This is because each relatively massive dust particle is a separate satellite of the Sun, and particles further from the Sun orbit more slowly.

The other tail consists of rapidly moving ions which, being much lighter, are affected more by the pressure of the solar wind. The ion tail is made visible not by reflected light but by emission of light as positive ions and electrons recombine. The ion tail is usually straight, but at times it can be observed to twist or kink very suddenly. This erratic behaviour is due to sudden variations in the magnetic field through which the comet is travelling.

During a total eclipse of the Sun, the Moon blocks out our view of the photosphere, the bright disk of the Sun. At this time, the relatively faint corona of the Sun can be seen, extending to about two solar radii from the edge of the photosphere (Fig. 6). The corona is a plasma, containing only about 10^{14} particles m^{-3}. By terrestrial standards, the corona would be described as a superb vacuum: the particle density in the vacuum of a TV tube, where the pressure is about 0.1 mPa, is about a hundred times greater. The temperature of the corona is very high, about 1 000 000 K. This is much hotter than the photosphere beneath. The source of this heating is not fully understood. However, this high temperature explains why ions in the corona can 'boil off' as solar wind, while the ions in the cooler photosphere are trapped by the Sun's gravitational field.

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Details: An image of an eclipse

Fig. 6

Coronal Mass Ejections

Observations made during eclipses have long shown turbulent disturbances of the solar surface. These are called flares and prominences and are particularly noticeable during times of sunspot maxima. The most spectacular events of this sort, studied in detail by SOHO, are Coronal Mass Ejections (CMEs). These are large amounts of plasma, threaded with magnetic flux, ejected through holes in the solar corona at speeds up to 500 $km\,s^{-1}$. These huge bursts of ionised matter, up to 10^{14} kg in mass, can affect us here on Earth in a number of ways. By electrically charging satellites, electronic equipment can be overloaded, and a number of satellites have been put out of action by CMEs. They can also have a direct effect upon us on Earth. In the sunspot maximum of 1989, a CME produced a surge of induced current which damaged transformers of the Hydro-Quebec power system, leaving eastern Canada and the northeast United States without power for more than nine hours.

Space probes such as SOHO study the Sun continuously and can give a warning whenever a CME is heading towards Earth. This gives about three days to prepare for any possible damage. However, CMEs are not totally destructive. As the ions meet the Earth's magnetic field and spiral down the field lines to the poles, they excite the molecules of the atmosphere and produce the beautiful effects of the aurora borealis and aurora australis, the Northern and Southern Lights (Fig. 7).

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Details: An image of the Northern and Southern Lights

Fig. 7

End of Article

Copyright Acknowledgements:

Fig. 2	From http://www.nsip.net/solarexplorer/tutorial.cfm
Fig. 5	© NASA. From http./antwrp.gsfc.nasa.gov.apod/ap040420.html
Fig. 6	From www.noao.edu/image_gallery/html/im0397.html
Fig. 7	From http://www.photolib.noao.gov. Collection of Dr Herbert Kroehl, NGDC.