The Sun and the Interplanetary Medium

Professor D.E. Blackwell

My own brief is to speak to you about the Sun and the interplanetary medium. In one sense this is going to be a difficult task because of the great range of these topics. For example, even the so-called quiet Sun is a source of detectable electromagnetic radiation with wavelengths from the X-ray region to the extreme radio region: it also emits a steady stream of assorted kinds of atoms, called the solar wind, and probably a stream of neutrinos. These phenomena, and there are many others, need a variety of techniques for their investigation and interpretation, so clearly my survey must be very selective and will have to omit all reference to many important aspects of solar physics. Nevertheless, it is a welcome assignment because so many distinguished British astronomers have made important contributions to solar physics at some time in their lives, and just a list of names makes impressive reading. Among the earlier British observers there were Wilson, Carrington, Lockyer, Fowler, Evershed, Huggins, Newall and Stratton, whilst among the theoreticians were Kelvin, Schuster, Milne and Eddington. These people helped to lay the foundations of the subject. Indeed, it has been said that Evershed in particular knew, and wrote about, almost all of the phenomena that we now study, and for the most part we are now simply filling in the details. It is of some of these details that I propose to speak now, and in doing so I should like to illustrate two particular theses. One is that the Sun is a reliable guide for the study of other stars, and is even having an influence on pure atomic physics. The other is that in the past the Sun has yielded many surprises, is still doing so and may be expected to continue to do so in the future.

Like all other branches of astronomy, solar physics depends upon fine instrumentation, and it is a tribute to the present vigour of the subject that so many new solar telescopes and auxiliary instruments of advanced design are appearing, chiefly in the United States, on the Continent and in Australia. The solar astronomer is plagued more than his stellar counterpart by poor seeing, and the biggest advances that have been made in ground based instruments have been directed towards reducing the part of the unsteadiness of the image that is due to air currents at the dome entrance and in the telescope itself. The fundamental idea, which I believe is due to Lyot and Kiepenheuer, is that the dome should be eliminated and the telescope mounted inside...
a second skin, that is separate from it but moves with it, the second skin being closed by a window so that evacuation is possible. An example of an evacuated telescope is the new solar installation at Sacramento Peak designed by Dr Dunn: this instrument has a quartz window of diameter 30 inches in front of a coelostat. Among other new observatories I should like to mention the Malta outpost of the Cambridge Observatories and the Swiss outpost of the Oxford Department of Astrophysics, both of them financed by the Science Research Council.

Actual solar data are more important that instruments, but before leaving observatories and their equipment I want to refer to one other somewhat unusual observatory, the solar neutrino observatory at Brookhaven. The background to this observatory is as follows. The solar energy is provided by the nuclear reactions that are proceeding in the central regions. In the past, these reactions have been investigated using laboratory data for the cross-sections, and theoretical models of the solar interior, without any expectation that direct observations of the conditions there might be made. However, it is known that some of the reactions should liberate neutrinos which, because they interact so weakly with other nuclei, are able to escape from the Sun carrying with them a substantial fraction of the total rate of energy output from the Sun. There is now a distinct possibility that the resulting flux of neutrinos at the Earth, probably about $10^7$ cm$^{-2}$ s$^{-1}$, should be detectable, and several experiments are being conducted at this time to detect these neutrinos. Among these are the experiments of Davis and his colleagues at Brookhaven, which are being made at a depth of nearly 5000 ft in a mine shaft using some 100,000 gallons of perchloroethylene as absorber. So far no neutrinos have been detected, but Davis has been able to place an upper limit on the flux which is about $1/7$ of the predicted flux: that is, were neutrinos present at the predicted rate of flow they should have been detected quite easily. This is an important discrepancy which I suggest might be resolved by a re-assessment of solar abundances. Apart from the nuclear cross-sections the predicted flux depends upon the adopted model for the internal structure of the Sun. This model depends upon the opacity of the solar interior which, in turn, depends upon the proportion of heavy elements, commonly denoted Z. Unfortunately, the value for Z for the calculation of opacity can only be obtained from spectroscopic investigations of the solar atmosphere, which will not necessarily have the same composition as the interior. I shall be speaking of solar abundances later in this talk, but I believe that this topic too is in a very uncertain state and it remains to be seen whether any drastic revision which might be coming is going to bring better agreement between the predicted neutrino flux and the upper limit of Davis.
This now brings us to the solar atmosphere. Most of the light that we see originates over the range of optical depth 0.2-2.0. We cannot see deeper because the higher layers are absorbing, and we cannot see higher because the atmosphere is too thin. This layer has a thickness of only about 100 km and a total mass of $10^{28}$ g which is some $10^{-10}$ of the mass of the Sun. If we compare the Sun to a sphere of 1-cm radius, the proportion of solar mass that we actually observe would correspond to a skin on our sphere of thickness $3 \times 10^{-11}$ cm, which is about 1 per cent of the radius of the hydrogen atom in its ground state. It is small wonder that we do not have an answer to every solar problem.

A glance at the solar disk even in white light at a time of good seeing shows that the physical state of its atmosphere is very complex. This is demonstrated by the particularly fine photographs of solar granulation obtained at Sacramento Peak, and of the chromosphere of the quiet Sun obtained in H-alpha at Anacapri. These photographs demonstrate the presence of small scale atmospheric motions. Motions on a larger scale have been found by Plaskett and others. Plaskett in particular has pioneered the quantitative study of the circulation of the solar photosphere through precise measurement of the small Doppler displacements of the spectral lines that they produce. The small scale motions especially have quite a profound effect on the photospheric spectrum, as is shown by photographs of the so-called wriggly Fraunhofer lines. Dr von Kluber at the Cambridge Malta station has even observed variations of Fraunhofer line intensity over the solar disk that are correlated with local magnetic fields. In the face of these complexities, and there are many others, one is tempted to enquire how reliable any interpretation of the solar spectrum can be.

This is not unimportant because the solar spectrum is the best known of all the celestial spectra, and the solar photosphere therefore provides the standard for all abundance determinations. Indeed, it might be hoped that because the equivalent widths of absorption lines can be obtained to an accuracy of about 1 per cent, it should be possible to get the abundances of the elements to this accuracy also. But for some years there has been some uncertainty about solar abundances which arises from a comparison between photospheric and coronal abundances. Just as it is possible to obtain photospheric abundances from absorption lines in the photospheric spectrum, so it is possible to obtain coronal abundances for a few elements from a study of the emission lines that they show in the coronal spectrum. Here, what we must do is to compare the energies in the lines with the energies in the neighbouring continuum. This kind of analysis was first done by Woolley and Allen in 1948, who showed then that the coronal abundance of iron, for example, is considerably greater than the photospheric abundance. Until a few weeks ago subsequent and
rather more refined comparisons of this nature have always given a similar result. There has never been much support for the belief that there really is such a large difference between abundances in so closely adjacent levels of the solar atmosphere, neither has there been much doubt about the coronal abundance. In these circumstances, what has gone wrong with the photospheric determination? Is there an error in the theory of absorption line formation, or are there errors in the transition probabilities that are needed to interpret the data? We at Oxford believe that the errors lie in the experimentally determined transition probabilities, which may easily be wrong by factors of ten or more, and that the most reliable way of determining such data is to measure the absorption produced by a column of vapour, as happens in the solar atmosphere. It is clear from the work already done that there will probably have to be drastic revisions in currently accepted solar abundances, which will have repercussions even on the interpretation of the neutrino experiment. Indeed, it seems to us that one of the most important needs at present in solar and stellar atmosphere work is for values of transition probabilities that are reliable to at least 10 per cent, and also, incidentally, more reliable values for damping constants. I have spoken of this matter in some detail because it illustrates the first part of my thesis, that there is a vital interaction between solar physics and pure atomic physics.

In discussing the Sun one must speak, if only briefly, of magnetic fields and sunspots. If it could be isolated from the Sun, a spot of diameter 30 sec arc would have an absolute magnitude of about — 16.7, which means that it is the second brightest object in the sky, with a total brightness that is some 50 times greater than that of the full Moon. Yet in spite of this we know very little about the origin and behaviour of sunspots and even now there is still not a generally accepted model of a sunspot atmosphere. Quite apart from the pure spectroscopy we have in a spot a wonderful opportunity to study the essentials of magnetohydrodynamics: for example, it should be possible, at least in theory, to obtain both the direction of material flow and the direction of the magnetic field at each point in the spot atmosphere. Such measurements pose very difficult and complex problems which have been solved properly only during the last two or three years by Miss Adam who has followed the technique originally suggested by Dr Treanor: her results are going to be very interesting, but I intend to leave it to her to describe them to you at some future date.

Immediately over the photosphere are the very complex and difficult chromospheric and coronal regions which have been the subject of many eclipse expeditions from this country. Britain has a fine record of such expeditions going back well into the last century, most of them financed by the Royal Society under the guidance of the Joint
Permanent Eclipse Committee. Many of these expeditions were made at a time when this interest was shared by only a few astronomers and I personally am very sad to see this Committee disbanded just when eclipse work is regarded by other astronomers as a very important activity. Now there is the additional interest of using a rocket to make observations in the ultra-violet, and the possibilities here are shown by the flash spectrum that was obtained at the last eclipse by a consortium that included Dr Wilson and others in the Astrophysics Research Unit at Culham. An interesting feature of this photograph is the great extension of the corona in Lyman-alpha which the observers attribute to resonance scattering of Lyman-alpha radiation by the very small amount of neutral hydrogen in the corona.

The subject of solar radio astronomy was started by Hey with his observations of radio emission in the 4–6 metre band from a solar flare. The observation was made during the war using army radar equipment, and Hey reports in his letter to Nature four years later that they ‘were able to follow the source (of interference) continuously in bearing and elevation, and observation through the equipment telescope revealed that they were looking directly at the sun’. Immediately after this letter is one from Stratton, pointing out the probable connection with flares observed at this time and a great storm. Since this time solar radio astronomy has developed greatly, the latest application being by Muhleman and by Seielstad to the measurement of the Einstein light deflection in the gravitational field of the Sun. This experiment need not be done at a time of total eclipse, but it is only necessary to have a suitable radio source in a position near to the Sun. Of course, in the radio region, unlike the optical region, there is also a deviation due to refraction by the coronal free electrons. This can be allowed for by using two radio wavelengths, when one also obtains the variation of electron density with distance from the Sun in the corona. If \( \gamma \) denotes the ratio of the measured deflection to the value predicted by Einstein the final result of Muhleman from his October 1969 work is that \( \gamma = 1.04^{+0.15}_{-0.10} \), the two independent experiments of Seielstad and Muhleman agreeing very well. Of course, what we should like to know is whether the Einstein theory can be distinguished from the Dicke theory: the latter leads to \( \gamma = 0.93 \) but I leave it to you to judge the significance of the deviation from the measured value of 1.04. Incidentally, the electron densities given by this radio technique differ considerably from those found optically, but this could be explained by the complexity of the corona, as is particularly shown by the photographs obtained by Dr Laffineur at the last eclipse in Mexico.

I should like to conclude with a short exposition of the history of
coronal studies. Most of the light that one sees on a photograph of the corona is due to electron scattering. However, this theory is not entirely adequate because the coronal spectrum shows some weak Fraunhofer lines, whereas on the scattering theory it should show a continuous spectrum only. Before the war, Grotian suggested that these intrusive Fraunhofer lines indicate the presence of a component of coronal light that is due to scattering by dust in interplanetary space. Grotian also realized that a difficulty with this explanation was that the dust component is observed near to the solar disk, and it was thought that this implied that the dust also is close to the solar surface, where it surely would be vapourized. The way out of this difficulty was shown by Allen and van der Hulst independently who suggested that the dust particles scatter light strongly in a forward direction so that they need not be located close to the Sun. At this stage, the zodiacal light was drawn into the discussion because it was already known in 1953 that it is actually the outer part of the solar corona, and there followed a series of expeditions from both Oxford and Cambridge (and here I should mention the names of Wolstencroft, Dewhirst, Ingham and Petford) to determine the electron density all the way out to the orbit of the Earth, and the brightness of the dust component out to elongation 180°. The last of these expeditions gave a maximum value for the density of electrons at 1 A.U. of 16 cm⁻³ ± 20 cm⁻³. With data such as these in mind it was possible to discuss models of the corona and it immediately became clear that a static model is not possible because its pressure would be greater than the pressure of the interstellar medium. This led Parker to suggest his celebrated solar wind model, in which the material of the corona is moving out at a speed of a few hundred km s⁻¹, a model that was triumphantly vindicated by direct observation from Explorer 10 and the Venus Probe, Mariner 2. This discovery of the solar wind came as a surprise, but in fact Biermann had already deduced from the behaviour of comet tails and particularly the observation that a tail does not usually lie along the radius vector to the sun, that there must be a continuous flow of material from the Sun. The existence of the interplanetary electrons, and their outward motion, is also shown by the observations of radio-scintillation made by Hewish, and it is even possible that if the beginning of space research had been delayed by two or three years, Hewish might have discovered the solar wind. In the light of subsequent developments, one further phenomenon observed by the Cambridge eclipse expedition to Khartoum in 1952 is of interest. This observation is that the corona has a large infra-red excess at a wavelength of about 2 microns. This infra-red excess has been subsequently found by other eclipse observers, and I refer particularly to the more detail observations of
Peterson. The excess is at least partly due to thermal emission from dust particles in the vicinity of the Sun, and it is natural to interpret the details in the Peterson observations, as he himself does, to emissions from the various kinds of particle in zones just outside the distances at which they are vapourized. Infra-red excesses such as these are now commonly observed in stars and even in extra-galactic nebulae, and such studies have inspired the construction of new large flux collectors, such as the new S.R.C. one, to be used for more detailed observations.

Here are at least four recent surprises: radio emission, revision of abundances, infra-red excess, solar wind. Now that the Sun is being studied even more intensively by devices such as the American Orbiting Solar Observatory I am sure that we can expect even more, but at least I hope I have demonstrated the vigour and worthwhileness of solar physics. As yet, we understand so little of the Sun. That being so, how can we hope to understand the stars?