europhysics news
BULLETIN OF THE EUROPEAN PHYSICAL SOCIETY
Solar Physics

J.A. Volume 13 Number 1 January 1982

Solar Physics in EPS

On the initiative of the Board of the Solar Physics Section of the Astronomy and Astrophysics Division, this special issue of *Europhysics News* on solar physics has been prepared. The Solar Physics Section was established in 1976 within the EPS in order to bring physicists and astrophysicists together, and contribute to the maintenance of a greater contact across the disciplines.

Although the total number of solar physicists in Europe is substantial, the communities in most countries are small. Accordingly, the Section encourages collaboration, organizes meetings and provides a forum for the exchange of ideas. Workshops on well selected subjects have proved to be an important part of the activities and, with a view to achieving an efficient use of resources in the future, the Section organized the workshop "Near Future Plans for Solar Research" in Oxford on 10 and 11 April 1981 (see C. Jordan and I.W. Roxburgh, *Europhysics News,* 12, 8/9, p. 12). This workshop gave insight into the national plans of seventeen countries from all parts of Europe.

Based on the remarkable consensus that emerged concerning priorities for future study, the Section Board asked R.M. Bonnet (Verrières le Buisson), C. Jordan (Oxford) and P. Maltby (Oslo) to prepare a consolidated summary of the findings. Their report entitled "Solar Physics in Europe; recommendations for the 1980's" has recently been endorsed by the Solar Physics Section Board. In it is outlined the current state of the physical problems, and recommendations are presented for immediate action using ground-based observations, space observations, data reduction and analysis as well as theory. By giving advice to future research in this way the Solar Physics Section hopes to encourage a continued significant European contribution to the field.

Development of Solar Physics in Europe

Per Maltby, Oslo
(Institute of Theoretical Physics)
Chairman of the Solar Physics Section of EPS

Solar physics, indeed, the whole field of astrophysics, began in 1611 when the first observations of sunspots through a telescope were announced. The honour of this discovery was shared by: J. Goldsmid (also known as Fabricius) in Holland, G. Galilei in Italy, C. Scheiner in Germany and T. Harriot in England. The priority of publication belongs to Goldsmid, but it is clear that Galilei had noticed spots on the solar surface in July 1610 already.

Development in the 19th Century

Advances in solar physics have usually occurred following the development of new types of instrumentation or new physical concepts. For example, the sunspot observations by Galilei and others were made possible by the invention of the telescope by Lippershey and his associates in Holland. In some cases, however, results emerged from the analysis of synoptic data accumulated during a large number of years. For more than two centuries, progress in solar physics was very slow. Then in 1843, H. Schwabe, analysed his sunspot observations and found that the "spottedness" of the solar surface varied with a period of about 10 years. An accurate determination by Wolf in 1852 gave an average period of 11.1 years for the solar cycle.

As noted already by Galilei, individual sunspots have lifetimes ranging from less than one day to several months. Using observations of long lived sunspots, R.C. Carrington was able to determine quite accurately the solar rotation and its deviation from that of a rigid body in 1863. His discovery that the average latitude of sunspots decreases steadily from the beginning to the end of each 11 year cycle, supplied the first indication of a connection between solar rotation and the occurrence of sunspots. This drift was also investigated by G. Spörer, who noted that the number of sunspots was remarkably low between 1645 and 1715, a period that was studied in detail by E.W. Maunder in 1894 and is usually referred to as the "Maunder minimum". The phenomenon suggests that the solar cycle itself is variable, a possibility that has received considerable publicity in recent years in connection with studies of the climate of the Earth.

The next great instrumental development was the introduction of the spectroscope by Fraunhofer who, in 1814, published a description of the solar spectrum based on visual examinations. The investigation of stars by physical methods began in 1859 when Kirchhoff and Bunsen discovered the significance of the Fraunhofer lines in the solar spectrum. The discovery of helium as a new chemical element was based on observations of the D_3 line by Janssen during the eclipse of 1868. In passing, we note that it was not until 1895 that Ramsay succeeded in isolating helium from terrestrial minerals. The first detailed mapping of the solar spectrum was based on Rowland's perfection of the concave grating and was published in 1897.

The first successful photograph of the Sun was taken by Fizeau and Foucault in 1845. The nature of prominences (i.e. cold and dense regions extending up to, say, 40000 km or more in the solar atmosphere) was a subject of controversy until photographic records obtained by de la Rue and by Secchi during the solar eclipse in 1860 identified them as being of solar origin. It was shown by Janssen and by Lockyer in 1868 that sufficient energy is emitted by prominences for them to be observable outside the periphery of the eclipsed Sun if

 ISSN 0531-7479

a spectroscope centred on a strong spectral line used.

Solar Physics in the 20th Century

George Ellery Hale was responsible for shifting the centre of gravity in solar physics research from Europe to the USA. He detected in 1908 the characteristic Zeeman splitting of spectral lines and established the existence of strong magnetic fields in sunspots (magnetic induction about 0.3T). Continuing synoptic observations of sunspot magnetic fields, he was able to show that the 11-year solar cycle corresponds to a 22-year magnetic cycle. The contribution to solar physics by Hale and his collaborators were so important that the period 1890-1930 is often referred to as the Hale-Mount Wilson era in solar physics.

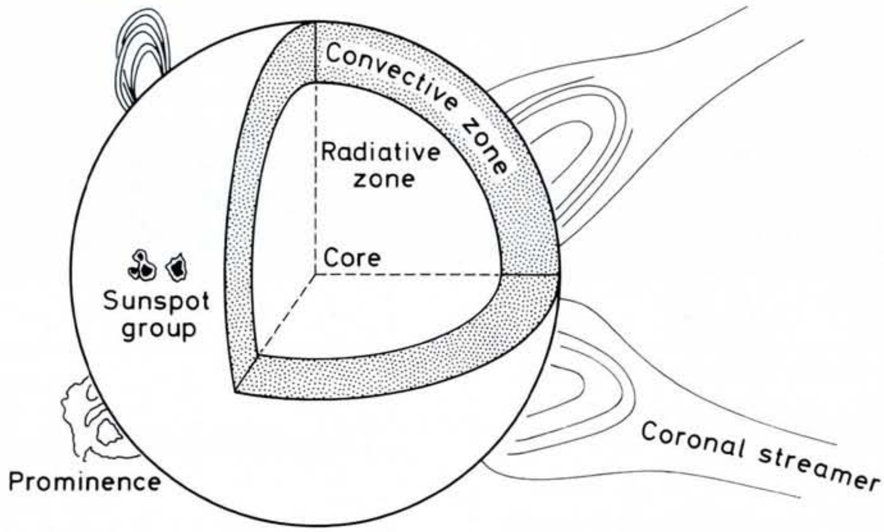
During the 1920's it became possible through the development of quantum theory to understand quantitatively the processes of emission and absorption of light by atoms. The theoretical investigations by Eddington, Milne, Pannekoek, Rosseland and Unsöld formed the basis for the highly significant European contribution to the interpretation of solar and stellar spectra.

Since 1930, through the invention of the coronagraph by Lyot and his accurate measurements of coronal lines, Edlén solved the outstanding problem of line identification. In 1941 he interpreted these lines as caused by transitions of highly ionized atoms and showed that the kinetic temperature in the corona was 1-3 MK. The temperature of the corona varies both spatially and temporally and is much higher than the 6000 K of the visible surface layers. In consequence, it cannot be the radiation field which maintains it.

On the theoretical side Unsöld, in 1930, created the theory of convective streaming; shorly afterwards, Rosseland called attention to the astrophysical significance of turbulence and Siedentopf and Biermann developed the hydrodynamic mixing-length theory for the transport of energy in the convection zone. The observed solar granulation can be ascribed to the instability of the surface layer of the convection zone.

The theoretical basis for magneto-hydrodynamics and its application to the Sun was worked out in Europe by Alfvén, Cowling and others in the 1940's. Of particular importance was Alfvén's prediction that waves can travel along magnetic lines of force in a conducting material, with a speed that depends on the magnetic field induction and the gas density.

Solar radio astronomy was introduced in 1942 when Hey in England and independently Southworth in the USA detected radio signals from the Sun. Hey's observations of strong non-thermal disturbances were unexpected and gave rise to intensive study, by the Australians in particular, of radio disturbances in the solar corona and associated plasma physics problems.



Sketch of the interior and some features in the atmosphere of the Sun.

Taking the high electrical conductivity into account, Cowling in 1946 drew attention to the fact that theoretically, the magnetic field of a sunspot would take 1000 years to diffuse, whereas its observed lifetime ranges from less than a day to several months. The solution to this riddle was advanced by Steenbeck and Krause who, in 1969, pointed out that turbulence makes an important contribution to the twisting of the magnetic field so that the effective conductivity is decreased by a factor of about 10^4. This work stimulated interest in the solar dynamo theory where European contributions have been significant.

The realization of the existence of a solar wind of electrons, protons and a smaller number of heavier particles came gradually. The first suggestion was made in 1896 by Birkeland, who advanced the idea that charged particles from the Sun were the cause of the aurora borealis. In 1951, Biermann put forward the hypothesis that the plasma tails of comets are driven away from the Sun by a continuous stream of solar particles. Following discussions with Chapman, the first theory for the solar wind was worked out by Parker in the USA in 1959, and showed that for coronal temperatures above 0.5 MK, a continuous outflow will occur, whereas for lower temperatures, there will be an accretion.

The progress in solar physics that has been made over the past twenty years reflects the vitality of the field. A complete description of this development will not be given here, but a few of the highlights will be mentioned:

— The discovery by Davies and his collaborators in the USA that the flux of electron neutrinos from the Sun is a factor three smaller than predicted by the standard model of the solar core, has triggered a series of interesting suggestions, including the possibility of an oscillation between neutrino states.

— Initiated by the observations by Deubner in 1975, the dynamical oscillations of the Sun have been measured with such precision that it is possible to put constraints on solar models. Hence the name "solar seismology".

— The detection with instruments on the Solar Maximum Mission and on the Nimbus 7 satellite of variations in the solar radiation suggests blocking by sunspots.

— One of the most important observations in recent years is that magnetic fields fragment and concentrate into separate flux tubes, where the magnetic induction is 0.1-0.2 T, according to Stenflo and others.

— The outstanding problem of the heating of the solar corona has been attacked in different ways. Observations show that acoustic waves with periods between 150 s and 400 s cannot compensate for radiative and conductive losses. Large mass motions detected by the US Naval Research Laboratory rocket flights may throw new light on the problem.

— Observations show that high speed streams in the solar wind originate in coronal holes, i.e. regions with low X-ray emission, which were first noted by Waldmeier in 1957 (and called "Löcher").

— Observations strongly suggest that solar flares originate in the corona through the release of magnetic energy. The presence of nuclear reactions has been confirmed by the detection of the 2.23 MeV gamma-ray line.

Present State of European Solar Physics

European groups active in space research have, over the past decade, been involved in experiments on the OSO-8 and the International Sun-Earth Explorer satellites, in the Apollo programme, and in the Solar Maximum Mission. Several experiments from European groups have been accepted for flight on the Space Shuttle. Thus a small but healthy community exists in Europe in solar space research.

Ground-based solar observatories in Europe are mostly run by a single university or institution, and the lack of a large European solar facility at an excellent site is a recognized weakness. This led to the establishment in 1969 of the Joint Organization for Solar Observations (JOSO), which has considerably increased the cooperation between the solar physicists. JOSO has tested some forty sites in southern Europe and has reached agreement on the superiority of the Canary Islands sites on La Palma and Tenerife. Phase A of the feasibility study for a large European solar telescope has recently been completed.

Solar radio astronomers have joined forces in the Committee for European Solar Radio Astronomy (CESRA) and are using to good effect the radio astronomy observing facilities within Europe. There is, however, no European equivalent of the Very Large Array in the USA.

The early rocket programmes led to a great interest in extreme ultra-violet and X-ray spectroscopy in several countries, and it was possible to be involved in space projects even when the hardware was not developed in Europe. In most other disciplines of solar physics, European groups continue to maintain a high scientific standard.

Diagnostics of the Solar Interior

Douglas Gough, Cambridge

(Institute of Astronomy and Department of Applied Mathematics and Theoretical Physics)

Our basic ideas about the structure of the solar interior come mainly from theory, in which there are many simplifying approximations and assumptions. Some of these are well established, but others are quite uncertain. It is a task of the solar physicist to evaluate the implications of the uncertain assumptions and to attempt to test them by observation.

The most fundamental approximation is that the Sun is spherically symmetrical and in hydrostatic support. This is well borne out by observation, and is an extremely accurate first approximation for determining the vertical balance of forces. Any deviation from hydrostatic support would lead to a dynamical relaxation on a timescale of an hour or less, and the Sun is observed not to change its shape or size on that timescale to about one part in 10^5. Low amplitude oscillations are observed, however; their most immediate importance is their diagnostic power, which is discussed below.

The horizontal balance of forces is quite a different matter. It was shown early in this century by Eddington and von Zeipel that unless a force or acceleration that breaks spherical symmetry has a very special form, it cannot find a reaction to balance it. Therefore it would induce material motion. This is true of rotation, for example, which induces large-scale circulation. The consequences of that circulation are difficult to ascertain, but there is bound to be some redistribution of the chemical elements and angular momentum.

In the theory of the evolution of solar-type stars, material mixing by circulation currents is normally ignored. Thus, for example, unless there is thermal convection, the products of nuclear reactions are assumed to remain *in situ*. This is crucial to evaluating the subsequent evolution of the star, in particular, the rate at which a star evolves from the main sequence once hydrogen is exhausted from its centre. It is evident that if the hydrogen fuel were replenished from the cooler envelope by mixing, the main-sequence lifetime of that star would be prolonged. The ages of globular clusters, which are used in estimating the ages of galaxies, are measured by comparing with theory the observed turnoff from the main sequence. Thus our astronomical timescale is intimately linked with the assumptions upon which the theory of stellar evolution depends. It is important, therefore, that the predictions of that theory be tested as carefully as possible, and at present our best opportunity for really delicate testing is comparison with the Sun.

The structure of a star is not determined solely by the dynamical forces. It depends also on the thermal balance. Thus it is necessary to know how thermal energy is created and transported. This, in turn, requires knowledge of the nuclear reaction rates and opacities, and a theory of convection. It is also necessary to know the equation of state. Clearly, any model of the Sun must produce the observed photon luminosity and provide a flux of neutrinos that does not exceed the upper bound, set by observation.

Calibration of Standard Solar Models

It is usual to consider as model, a theoretical stellar body of the same mass as the Sun that, from an intitially homogeneous chemical state, evolves with time owing to the nuclear transmutations in the core. The initial chemical abundances X, Y and Z of hydrogen, helium and heavy elements are in some sense undetermined parameters, though one does have some idea of their values. The relative abundances of the heavy elements are usually taken from spectroscopic observations of the solar photosphere and measurements of meteoritic abundances. As $Y + Y + Z = 1$, only two of these parameters are independent. There is also at least one, and usually only one, explicitly arbitrary parameter in the formula for the convective heat flux (α). Reynolds stresses are usually ignored.

The parameters Z and Y (say) and α are adjusted so as to give the correct luminosity L and radius R of the Sun now. As there are three parameters to adjust for only two observations, a one-parameter sequence of models results.

Models of the present Sun have a radiative interior and a convective envelope. In practice, as the mixing-length parameter α affects directly only the outer convective envelope, which contains very little mass, conditions in the interior are hardly influenced by it. Thus, roughly, α determines R, and L is determined by the chemical composition. It is best, therefore, to label the sequence of models by a chemical abundance, and here I choose Z. It is thought that the best value of Z is about 0.018, which yields $Y \cong 0.25$.

The time taken for the Sun to approach thermal balance and the time for the principal energy generating nuclear reactions to reach local equilibrium are short compared with the Sun's age. Moreover, the model of the present Sun is quite insensitive to the thermal structure adopted as initial conditions. Consequently it does not matter if the initial temperature distribution does not faithfully represent our ideas of what conditions were actually like when the Sun arrived at the main sequence.

Aside from a boundary layer only 10^3 km thick, the convective envelope is very close to being adiabatically stratified. Thus the purpose of the calibration of α is simply to attach the photosphere, through that boundary layer, to that adiabat which matches smoothly onto the radiative interior.

The evolution of the models is such as to lead to a gradual rise in luminosity with time from an initial value of about 70 per cent of the present value. Radius changes are smaller, and depend on the convection theory adopted: an increase of about 15% is not atypical. The models appear to be stable to thermal instabilities, and as the thermal relaxation time is much less than the nuclear evolution time, a thermal balance between the energy generation rate in the core and the luminosity at the photosphere is accurately maintained.

Solar Neutrino Problem

The description above summarizes briefly the evolution of what is called the standard solar model. Most stellar physicists probably believe that it is quite an accurate first-order representation of the actual Sun. Nevertheless, as is now widely known, when a plausible value of Z is