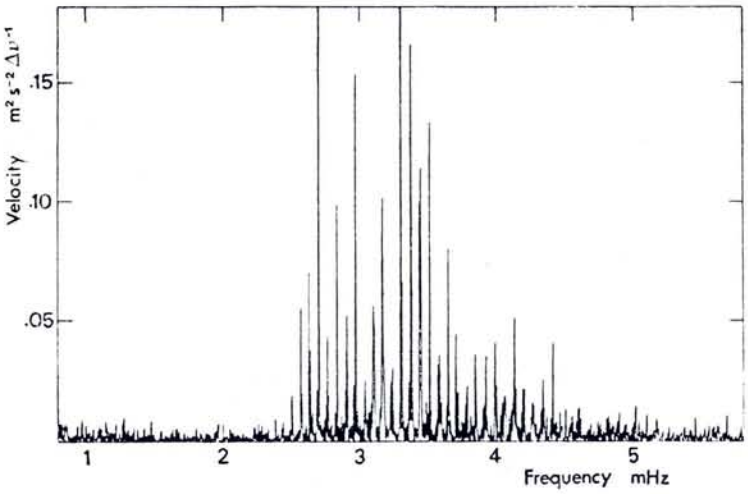

*Fig. 2 — Power spectrum of integrated Doppler shifts of 120^h continuous data obtained at the South Pole by G. Grec, E. Fossat and M. Pomerantz (*Nature, **288** *(1980) 541). The almost uniformly spaced peaks are composed of groups of modes of alternately odd and even degrees. The spacing is roughly four times the sound travel time from the centre to the surface of the Sun.*

sitive to conditions where the neutrinos are produced.

It must be pointed out that it has not yet been possible to obtain perfect agreement between theory and observation. Therefore one must be cautious in drawing conclusions from the analysis.

Rotational Splitting of Modes of Low Degree

The rotation of the Sun causes standing waves to precess, which is manifest as a frequency splitting of otherwise degenerate modes of like degree. The magnitude of the splitting is an average of the angular velocity in the solar interior, that average being weighted differently for different modes. Thus a knowledge of the splitting for a sufficiently wide selection of modes could teach us about the distribution of angular momentum within the Sun.

The first hint of rotational splitting was obtained by the Birmingham group. It was announced at the IAU Colloquium 66, which was held at the Crimean Astrophysical Observatory last September. The results are difficult to interpret, because modes that should not be detectable appear to be present in the data. Therefore we are not yet sure what the measurements imply.

More recently, rotational splitting appears to have been detected in oscillations of the limb-darkening function observed by R. Bos and H.A. Hill at the University of Arizona. Acoustic modes and internal gravity modes of low order and low degree have been measured, and from the splitting it has been possible to estimate the solar rotation. The angular velocity rises, probably monotonically, with depth, and in the core could be seven times the surface value. The results permit a rough estimate of J_2, the quadrupole moment of the external gravitational field. The value is about 6×10^{-6}, and is just sufficient to be relevant to observational determinations of the parameters appearing in post-Newtonian representations of the gravitational field.

Future Prospects

Aside from neutrino observations, the most likely means by which we might probe the solar interior is seismological. Already we have inferred that the Sun has a deeper convection zone than had previously been believed, and that the core of the Sun is possibly rotating up to seven times faster than the photosphere. Theoretical experiments have revealed that with not much more data than is presently available, it would be possible to measure the density stratification throughout the Sun to an accuracy of one or two per cent. Thus we are offered the possibility of measuring the inside of a star with a precision that has never before been envisaged.

FURTHER READING

1. Bahcall J.N., Solar neutrinos: theory versus experiment. *Space Science Reviews,* **24** (1979) 227-251.
2. *Non-radial and Non-linear Stellar Pulsation,* Eds. H.A. Hill and W.A. Dziembowski, Lecture Notes in Physics Vol 125, (Springer, Heidelberg) 1980.
3. "Physics of Solar Variations", Ed. V. Domingo, Proc. 14th ESLAB Symposium, *Solar Physics,* **74** (1981) 1 and 2.

Origin of the Solar Cycle

Manfred Schüssler, Göttingen

(Universitäts — Sternwarte)

The Sun is not a dull sphere of luminous gas, it is active and variable over a considerable range of spatial and temporal scales. Solar activity shows up in the appearance and decay of sunspot groups and bright facular regions, the formation, fading or eruption of prominences, the explosion of solar flares, one of which releases as much energy as would be produced by a 1000 MW power plant working for millions of years. Solar activity influences the earth through changes in the Sun's luminosity, by modulation of the solar wind and its interaction with the earth's magnetic field, and by energetic particles as well as UV radiation changing the conditions in the upper atmosphere.

Superimposed on all small scale spatial and temporal fluctuations is a quasi-periodic time modulation of activity with a period of roughly 11 years, the solar cycle. Fig. 1 shows the variation of the mean sunspot number (taken as a convenient measure of solar activity) from 1750 until today; the 11 year cycle and a modulation on a longer timescale is easily discernible. The variation of the ^{14}C production rate with solar activity allows the solar cycle to be traced back 8000 years into the past through the analysis of tree rings. Throughout this time the cycle continued to operate, apparently disturbed by a number of periods of very low activity.

Activity is concentrated into two belts in latitude, one on each hemisphere, which drift from mid latitudes towards the solar equator in the course of the cycle. It has become clear that solar activity is of magnetic origin and can only be understood by treating the electrodynamics of electrically conducting gases, i.e. plasmas. Let me stress a few of the most important results that any theoretical model must accommodate:

— The polar magnetic fields of the Sun change their magnetic polarity around activity maxima. Consequently, the magnetic period of the solar cycle is 22 years. This is supported by observation of the polarities of sunspot groups ("polarity rules").

— There is a small-scale component of the distribution of active regions which is not confined to the activity belts and seems to vary in antiphase with the big active regions while containing at least the same amount of magnetic flux.

— The non-spot magnetic fields are concentrated into narrow "flux tubes" with high flux density (100 - 200 mT in the solar photosphere).

— The brightness of sunspots varies during the cycle, darker spots appearing predominantly around activity maxima, brighter spots around activity minima.

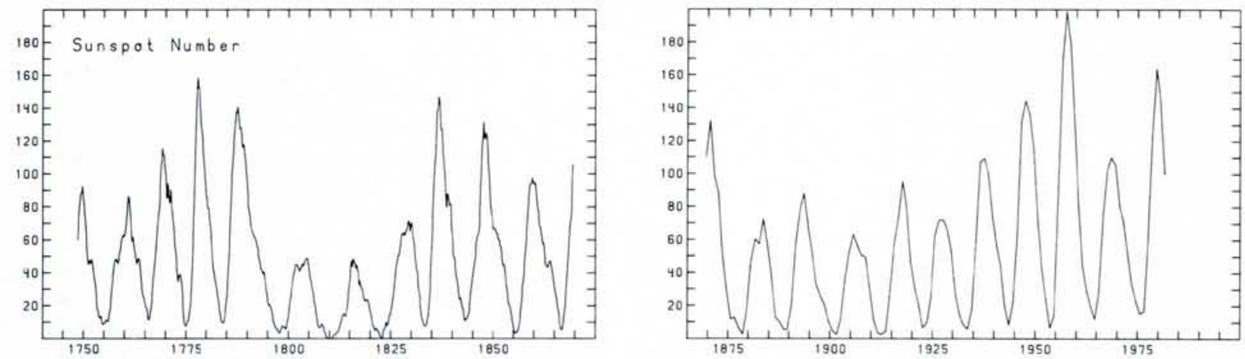

Fig. 1 — Monthly sunspot number as a function of time between 1749 and 1980. The 11-year-cycle is clearly discernible together with a longer period modulation of the height of the maxima. (Courtesy: A. Wittmann)

— Each activity belt is associated with a zone of higher velocity of rotation which drifts toward the equator together with the spot zone.

Understanding theoretically the "machine" responsible for the phenomena is not easy for a number of reasons:

a) It is observed that the magnetic flux producing activity enters the visible layers from below, i.e. from a non-observable region. Because of the high electrical conductivity of the solar plasma, the Ohmic decay time for a magnetic field in the static case is of the order of 10^{10} years — more than the age of the Sun. The timescale for polarity changes of the observed field is only 22 years; consequently, the fields cannot arise from a stored "fossil" field but have to be produced by dynamical processes which take place in a region obscured from direct observation.

b) These processes are almost certainly associated with mass motions in the solar convection zone. (Throughout the outer 30% of the Sun's radius, energy is transported by convection rather than radiation due to the ionization of hydrogen. The uppermost layer of convective cells is observable as the "granulation" structure of the solar photosphere.) The hydrodynamics of (turbulent) convection is poorly understood, even less if magnetic fields and rotation come into play. Thus, we cannot deduce easily from theoretical principles.

c) Until recently, the Sun was the only observed example of a star with cyclic activity, and is still the only star whose surface can be observed with high spatial resolution and where the interaction of rotation, convection and magnetic field can be studied in detail.

These shortcomings are responsible for the fact that there are quite a few more or less reasonable "theories" of solar activity on the market which presently cannot be exactly proven or disproven. They are all based on the magnetohydrodynamic (MHD) approximation, which combines the hydrodynamic equations with Maxwell's equations neglecting the displacement current (i.e. filtering out electromagnetic waves). MHD is a good approximation for the magnetic phenomena in stellar convection zones.

Concentration of Magnetic Fields and Topological Pumping by Convection

Magnetic fields in a convecting or turbulent body of fluid which is a good electrical conductor quickly display a strongly intermittent structure with strands of field of high flux density embedded in nearly field-free regions. This has been demonstrated by observations of the structure of the solar photospheric field as well as by extended theoretical considerations and numerical simulations. Convective cells exclude magnetic fields from the region of closed stream-lines, push them towards the edges of the cells, thereby concentrating them to a magnetic energy density at least as high as the kinetic energy density of the flow. We have good reason to assume that most of the magnetic field throughout the whole solar convection zone exists in the form of concentrated fields; i.e. we have to deal with an ensemble of flux tubes. These tubes locally can strongly modify the convective flow and any comprehensive theory has to include the non-linear character of this interaction.

Another potentially important effect of convection on magnetic fields is topological pumping. Consider the structure of the solar granulation: isolated upwelling regions are surrounded by a multiply-connected network of downdrafts. The net effect of such a pattern on magnetic field lines is a tendency to "pump' them towards the bottom of the convecting layer. This effect competes with magnetic buoyancy (see below).

Magnetic Buoyancy and Related Instabilities

A magnetic flux tube is in pressure equilibrium with the surrounding medium if

$$P_e = P_i + B^2/8\pi \quad (1)$$

i.e. the external gas pressure balances the internal gas pressure plus the magnetic pressure. Using the equation of state for ideal gases and assuming, for simplicity, the temperatures to be equal inside and outside, we find from (1) that the density is reduced inside the tube with respect to the external medium. The Archimedian principle tells us, then, that the flux tube is buoyant and will begin to float upwards. Associated with magnetic buoyancy is a certain class of instabilities.

Consider a layer of magnetic field underlying a non-magnetic layer under the influence of gravity. The magnetic forces add to the pressure force in supporting material against gravity in the equilibrium situation. This equilibrium is unstable; after a small perturbation magnetic (light) material flows upwards, non-magnetic (heavy) material downwards. Detailed analysis of this magnetic Rayleigh-Taylor instability shows that the preferred modes lead to the formation of narrow flux tubes which afterwards float towards the surface, owing to their buoyancy.

Magnetic Field Generation by Differential Rotation

The Sun does not rotate like a rigid body; the solar equator rotates approximately 20% faster than the polar regions. Furthermore, from observation of solar oscillations it has been deduced that the angular velocity also increases with depth. It does not seem remote from these observations that the Sun has a core with an angular velocity considerably higher than the surface value. In a plasma with high electrical conductivity, induction effects force magnetic field lines to follow the motion of the material in which they are embedded. A shearing motion like differential rotation stretches the field lines in the direction of rotation and produces an azimuthal (toroidal) magnetic field out of a field with a meridional (poloidal) component. The dominant East-West orientation of sunspot groups and the polarity rules lend support to the interpretation of active regions as being due to subsurface toroidal magnetic flux tubes which have locally broken through the surface. Because the Sun is observed to rotate differentially, it is reasonable to assume that these flux tubes are produced by differential rotation.

Magnetic Field Generation by Helical Flows

Differential rotation can generate a toroidal field out of a meridional field, but is not able to regenerate this field and prevent it from Ohmic decay. Consequently, another process is needed to close the chain and allow for self-excitation. It is tempting to assume a certain flow pattern that twists the toroidal field in such a way that the net effect is a meridional component of the field. This leads to the formulation of the kinematical dynamo problem: Can we find a velocity field $\mathbf{v}(\mathbf{x}, t)$ in such a way, that the electrical field $\mathbf{v}\mathrm{x}\mathbf{B}/c$ drives a current j which amplifies the magnetic field **B**?

In 1955, E.N. Parker presented a conceptual picture of a possible dynamo process based on the influence of rotation on convective motions due to the Coriolis force. F. Krause, K.H. Rädler and M. Steenbeck gave a more firm basis to it in the framework of the electrodynamics of mean fields. It has become clear since then that the correlation between velocity and vorticity, called "helicity", is the key parameter determining the possibility of dynamo action of a flow. Helicity can be understood as a "rest of order" in an otherwise chaotic flow. Helical flows such as turbulent convection under the influence of a Coriolis force are able to sustain a dynamo and build possible candidates for the "missing link" of the solar cycle, producing meridional field out of toroidal field.

Furthermore, turbulent flows in some cases are shown to enhance the diffusion and dissipation of a mean magnetic field through the formation of structures with small typical length scale, leading to a reduction of the effective electrical conductivity for the mean field.

The observed fact that stellar activity increases with the rate of rotation lends some support to the idea of turbulent dynamo action because the efficiency of the process increases with angular velocity as well. Model calculations incorporating the combined effects of differential rotation and helical flows display cyclic behaviour and can reproduce the basic features of the evolution of the large scale magnetic fields during the cycle: reversal of the polar fields, migration of the activity belt towards the equator and polarity rules.

Tentative Conjecture

In view of all the uncertainties mentioned in the introduction, a coherent theory of the physics of the solar cycle has not been given until now. But in order not to leave the reader alone with a bundle of concepts we give a conjecture (see Fig. 2) of how the solar cycle could operate, a picture presently shared by at least a fraction of active workers in the field.

Consider the transition region between the solar core and the convective zone at a depth of ~ 200000 km from the surface. The observations of solar oscillations indicate that this zone is also a shear region between the slowly rotating convection zone and the much faster rotating solar core. This differential rotation produces a toroidal field, which is kept down by topological pumping until it has grown strong enough to escape by means of magnetic buoyancy or a related instability. Helical flows produced in that phase by the influence of the Coriolis force on the velocity field possibly close the dynamo chain and regenerate the meridional field. After the field has left the amplification region, it is lifted upwards by the combined effects of convection and buoyancy in the form of concentrated flux tubes which break through the surface eventually and build active regions of all sizes. In the meantime, differential rotation is already producing the toroidal field for the next half cycle from the regenerated poloidal field.

Fig. 2 — A possible sequence of processes related to the origin of the solar cycle

Region	Physical Description	Processes Related to Magnetic Field and Activity Cycle
Interface Zone	Transition between $\omega_{(core)}$ and $\omega_{(envelope)}$. Shear zone with possible turbulence driven by instabilities due to differential rotation.	Generation of toroidal field by differential rotation. Field is kept down by topological pumping until it has grown strong enough to escape owing to buoyancy and magnetic instabilities; formation of flux tubes. Helical flows produced in that phase regenerate the poloidal field.
Convection Zone	Nearly adiabatically stratified region. Energy is transported almost entirely by convection. The velocity field may consist of large-scale eddies as well as small-scale turbulence.	Flux tubes are transported, shredded and reformed by convection and buoyancy. Small fragments can be carried around by convection and appear later as small active regions randomly distributed over the surface.
Uppermost Convection Zone and Photosphere	Transition between energy transport by convection and radiation. Stratification is slightly superadiabatic in the upper convection zone and sub-adiabatic in the photosphere. Velocity field consists of supergranulation (scale ~ 10^4 km), granulation (~ 10^3 km) and small-scale turbulence.	Flux tubes suffer from local instabilities leading to loop formation, break through the photosphere and build active regions. Adiabatic downflow along the loops cools relative to the superadiabatic exterior and leads to an even stronger concentration of fields. Sunspots appear and are eventually disrupted by velocity fields.

REFERENCES

The interested reader is referred to:

1. Krause F. and Rädler K.H., *Mean-Field Magnetohydrodynamics and Dynamo Theory,* (Pergamon Press, Oxford), 1980.
2. Moffatt H.K., *Magnetic Field Generation in Electrically Conducting Fluids,* (Cambridge University Press, Cambridge) 1978.
3. Parker E.N., *Cosmical Magnetic Fields,* (Clarendon Press, Oxford) 1979.
4. Stix M., "Theory of the Solar Cycle", *Solar Physics* **74** (1981) 79-101.
5. Piddington J.H., "Solar Magnetic Fields and Convection. VII. A Review of the Primordial Field Theory", Eds. V. Bumba and J. Kleczek, *Proc. IAU — Symp. 71 Basic Mechanics of Solar Activity,* (Dordrecht) 1976, p.389.

Physics of the Solar Corona

Claudio Chiuderi, Florence

(Istituto di Astronomia, Università di Firenze)

The solar corona is the outermost part of the atmosphere of the Sun, a tenous, hot plasma extending outwards from slightly above the visible limb to well beyond the Earth's orbit. The denser part of this plasma, close to the Sun's surface, forms the corona proper, only visible during total solar eclipses or by means of special instruments, the coronagraphs, at least at optical wavelength. Typical values of the physical corona parameters are a temperature of the order of 1-2 x 10^6 K, with occasional localized increases up to a few times 10^7 K, and a number density in the range 10^8 - 10^{10} cm^{-3}.

Because of the difficulty of observing optically the solar corona, a rapid development did not take place until observations at different wavelengths made this part of the atmosphere more accessible. From the typical values quoted above, it is clear that the corona will emit at radio wavelengths as well as in the X-ray region. The terrestrial atmosphere is transparent to radio waves and opaque to X-rays, so that while coronal observations at radio frequencies can be made routinely, X-ray observations can be only performed from space, and our information is necessarily more fragmented in time.

The corona is in a state of continual expansion, the consequent outflow of matter constituting the solar wind, with an average flux of 3 x 10^{-16} g $cm^{-2}s^{-1}$, which corresponds to a total mass loss of ~ 10^{-14} solar masses per year. The properties of the solar wind have been studied *in situ* by artificial satellites from about 0.3 AU to 1 AU (1 AU ≅ 150 Mkm).

There are many reasons for our interest in coronal studies: the Sun is the only star in our vicinity, and the solar corona can be considered a giant plasma laboratory,