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Edited by B. N. Dwivedi and E. N. Parker
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Dynamic Sun

Dynamic Sun presents a modern, comprehensive, and authoritative overview of the Sun, from its deep core to the outer corona, and the solar wind. Each chapter is written by eminent scientists in the field of solar physics. Chapters deal with solar models and neutrinos, seismic Sun, rotation of the solar interior, helioseismic tomography, solar dynamo, spectro-polarimetry, solar photosphere and convection, dynamics and heating of the solar chromosphere, solar transition region, solar MHD, solar activity, particle acceleration, radio observations of explosive energy releases on the Sun, coronal seismology, coronal heating, VUV solar plasma diagnostics, and the solar wind. Solar observing facilities are presented in the last chapter. With a foreword by eminent astrophysicist Eugene Parker, the twenty chapters of this book are all fully illustrated and have comprehensive reference lists. The book covers all major topics in solar physics, and is suitable for graduate students and researchers in solar physics, astrophysics, and astronomy.

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Foreword

The Sun has posed a challenge to science since the telescope was first turned on it by Galileo, Schreiner, and others around 1610, and the Sun is no less mysterious today for all of our extensive knowledge of its structure. For the improving sensitivity and resolution of the observations, aimed at understanding the old mysteries, have led to the discovery of new mysteries. We have come a long way since 1610, with the overall static structure of the Sun evidently now firmly established. On the other hand, we have a long way to go to understand solar variability and magnetic activity in terms of the basic principles of physics. Observations and theory have progressed to a detailed description of the surface activity down to scales of the order of a hundred km. Unfortunately much of the action lies at still smaller scales, and the magnetic activity deep under the surface cannot be observed directly, so that inference replaces direct observation. Much of what we see at the surface defies theoretical explanation, e.g. the intense fibril structure of the magnetic field, the formation of sunspots, the remarkable penumbral structure of the sunspot, etc. We can describe these phenomena, but we cannot show yet why the Sun is compelled by the basic laws of physics (Newton, Maxwell, Boltzmann, Lorentz, *et al*) to produce them.

The review articles that collectively make up this book are intended as a survey of existing knowledge, which is substantial. It is the starting point for addressing the formidable scientific tasks that lie ahead. We should take heart, then, from the formidable scientific challenges that have already been overcome. For instance, a hundred years after Newton propounded the theory of mechanics and gravitation, the laboratory measurement of the gravitational constant G by Cavendish in 1797 provided the mass of the Sun. Avogadro's number was determined only in 1811. Then, followed by the development of thermodynamics and the kinetic theory of gases, the first self - gravitating polytropic models of the Sun were constructed in the late 19th century, indicating multi-million degree temperatures in the central region.

It must be appreciated that the elemental composition of the Sun was baffling for several decades, with the solar spectrum dominated by the lines of C,O,Ca,Na,Si,Fe, etc. on the one hand, while the theoretical models of the Sun required a molecular weight closer to H on the other. Theory of atomic physics and radiative transfer eventually made it clear that the Sun is mostly hydrogen and helium, with a photosphere too cool to excite their emission. The theoretical recognition of the negative hydrogen ion in the period 1940 - 1950 then explained the high photospheric opacity.

The advent of nuclear physics in the 1930's led to the realization that the thermal energy of the Sun is supplied by thermonuclear reactions in the core, dominated by the proton-proton chain and the carbon cycle. This laid to rest the traditional speculations that the energy was supplied by continuing gravitational contraction or by the infall of comets and asteroids.

Thus by 1950 the essential physics was in hand and theoretical models of the internal structure of the Sun could move forward, with continuing improvement in the calculation of the opacity of the solar gas as a function of density and temperature. Fortunately the recognition of helioseismology by 1980 provided a comprehensive precision test of the theoretical models of the solar interior. With the inclusion of such subtleties as the gravitational settling of the heavier ions, and the accumulation of He in the thermonuclear core, the theoretical model of the solar interior now provides the speed of sound as a function of radial distance that agrees everywhere with the speed of sound inferred from helioseismology to within the observational uncertainties of about one part in 500. So in the last decade we have achieved a firm standard model for the solar interior, based on the simple assumption that the original Sun was chemically homogeneous.

This state of affairs has proved essential in pursuing the observed solar neutrino emission from the thermonuclear core, the observed flux being only 0.3 - 0.5 of the theoretical value. Given that the internal structure of the Sun is now known accurately, it would appear that the discrepancy lies with the physics of the neutrino, initially assumed to be a stable particle. Neutrino oscillations between the e, μ, τ neutrino states are presently under intense experimental and observational study, with the rest mass of the neutrino already established experimentally as nonvanishing.

This brief but heroic history of solar physics is the platform from which we attack the contemporary array of mysteries of the Sun, originating in the vigorous and erratic generation of magnetic field in the convective zone. The convective zone is an unavoidable feature of a star like the Sun. It constitutes the outer 2/7 of the solar radius, across which the temperature falls from 2×10^6 K to 5.6×10^3 K (at the visible surface). The convection arises from the fact that below 2×10^6 K the radiation cannot handle the outward heat flux without the temperature declining outward so fast that the hot gas below continually changes places with the cool gas above.

The hydrodynamic antics of the convection have yet to be fully understood. Presumably the convection is responsible for the nonuniform rotation of the Sun, with a rotation period of 25 days at the equator and something in excess of 30 days at the poles. However, helioseismology shows the surprising fact that the surface rotation extends vertically downward to the bottom of the convective zone, with the radiative interior rotating approximately rigidly with an intermediate period of about 27 days. The best numerical hydrodynamic models of the convection have yet to duplicate this peculiar internal rotation profile, showing instead an angular velocity that is primarily a function of distance from the spin axis of the Sun.

The convective hydrodynamics becomes vastly more complicated and baffling when the magnetic fields are included. The essential point is that the gas is ionized and, therefore, on the large scale of the Sun, the gas cannot support any significant electric field in its own moving frame of reference. Consequently on all but the smallest scales the magnetic field is obliged to move bodily with the convecting gas, becoming enormously stretched and tangled. The magnetic fields appear to be sustained by stretching and winding in the nonuniform rotation and the convective cells.

One of the first puzzles to confront the theoretician is the very small resistive diffusion provided by the resistivity of the gas ($\sim 10^4$ cm^2/sec) and the rapid diffusion ($\sim 10^{11}$ cm^2/sec) required to understand the generation of magnetic fields over dimensions greater than 10^{10} cm in only a few years. One turns to the concept of turbulent diffusion, of the order of $0.1\lambda v$ for eddies with scale λ and velocity v. This automatically supplies diffusivities of the desired order of magnitude. However, with present estimates of the mean azimuthal magnetic field of $3\text{x}10^3$ Gauss or more in the lower convective zone, it appears that the magnetic field is far too strong to be carried about at random by the turbulent convection. Further it appears that the general magnetic field of the Sun is in an intensely fibril state throughout the convective zone. Estimates of the fibril intensity range from $1.5\text{x}10^3$ Gauss at the visible surface to thirty or more times as much at the base of the convective zone. The fibril form of the field implies an enhanced magnetic energy for a given total magnetic flux, and the question is why the field exists in this elevated energy state.

The vigorous interaction of neighboring fibrils in the tenuous atmosphere above the visible surface involves rapid reconnection and dissipation of magnetic energy in that tenuous atmosphere. Million degree temperatures are the rule at coronal levels and fast particle populations, occasionally up to 10^{10}eV per particle, are created in the larger flares. The background population of microflares and nanoflares generates an ambient and rapidly varying suprathermal particle population. The solar X-ray corona is one manifestation of this magnetic dissipation, while coronal holes and the fast solar wind streams are another. Coronal mass ejections and large flares arise from the large-scale convective distortion of the magnetic fields arching above the visible surface.

To reiterate the present state of solar physics, we understand enough of the basic principles of magnetohydrodynamics and plasma physics to describe the gross features of the observed magnetic activity. However, we do not understand enough to show how the activity follows from first principles. So we do the best we can, using magnetohydrodynamics in the large and more complicated plasma physical processes in the small, which can be very complex indeed in the intense thin current sheets of a flare, large or small. This volume provides a brief review of the intellectual properties presently in hand.

E.N. Parker
30 October 2001