The physics laboratory in the sky

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The Sun, by virtue of its large mass, size, and temperature, exhibits a variety of effects that are unknown in the terrestrial laboratory, thereby challenging the physicist to relate them to the basic principles of physics derived from the terrestrial laboratory. A number of solar phenomena are reviewed, with comments on the degree to which they are presently understood.

1. Introduction

THE Sun has played a prominent role in the development of physics since the times of Kepler and Newton, providing a window into phenomena unknown to the restricted scale of the terrestrial laboratory[1]. The Sun continues in that role today, providing mystery and opportunity in such diverse fields as lepton physics and magnetohydrodynamics. It challenges the experimental physicist to develop increasingly sophisticated tools for investigation and the theoretical physicist to see both new facets and extensions to basic laws of physics. With its large size and mass, it serves in two distinct roles: (i) as a passive self-gravitating thermonuclear object providing opportunities for testing existing laws of physics on a grand scale and (ii) as a large radiative, magnetic, fluid dynamics laboratory where nature displays astonishing dynamical phenomena, previously unknown and wholly outside conventional wisdom. The precision measurements of gravitational time delays in radio signals propagating close to the Sun are an example of the former, the sunspot is an example of the latter.

To begin with a review of past triumphs, recall that the gravitational field of the Sun is responsible for the motions of the planets in the manner described by Kepler's laws. The theory of mechanics and gravitation was put forth by Newton in 1686 with confidence because the theory described the motions of the planets, the Moon, etc. with remarkable precision.

Over the following two centuries, observations of the motions of the planets were refined, using the Newtonian theory of mechanics and gravitation to compute the slight gravitational effects of the planets and their moons on each other, and including the precession of the elliptical orbits, the precession of the planetary spin axes, etc. By the middle of the 19th century, the observations had become so precise that it was possible to show that the precession of the orbit of Mercury is of the order of 30 arc seconds per century greater than predicted by the Newtonian theory. By the end of the 19th century, the extra precession was established as close to 43 arc seconds per century. The only planet showing a significant anomaly was Mercury, closest to the Sun, where the presumably radial gravitational field of the Sun is strongest. Simon Newcomb suggested that the inverse square law of gravity might have to be modified.

The modification of Newtonian theory in 1916 by Albert Einstein's geometrized reformulation of gravitational theory, known as general relativity, brought theoretical mechanics into agreement with the observation by providing a theoretical precession larger than the Newtonian value by precisely 43 arc seconds per century. General relativity also predicted the small deflection of starlight passing near the Sun to be 1.75 arc seconds for a light ray grazing the surface of the Sun and quite different from the prediction of Newtonian gravity and special relativity theory. It also predicted a longer transit time for light or radio signals propagating across the deep gravitational potential well close to the Sun. Both of those effects have since been verified, the latter with great precision.

Now an obvious question concerns the uniqueness of Einstein's geometrical formulation of gravitational theory, based on the simplest lowest order terms of the metric tensor. There is a variety of other mathematical formulations that, like general relativity, reduce exactly to Newtonian gravitation in the limit of weak fields. They are in some ways more complicated than general relativity, involving an admixture of scalar field along with the tensor field. The Dicke–Brans–Jordan theory represents what was perhaps the most popular alternative. The theory introduces an extra free parameter defining the relative strength of the scalar field, thereby providing a wide range of precession of the perihelion of the orbit of Mercury. This is a qualitative difference from the unique value of 43 arc seconds per century predicted by general relativity. Dicke then pointed out that there is a possibility that the inner core of the Sun is spinning much more rapidly than the visible surface. The idea is based on the fact that newly-formed stars are observed to rotate rapidly, with periods of just a few days, as distinct from the 25-day period for the equatorial surface of the present middle-aged Sun (4.6×10^9 years). The initial angular

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momentum of a star is then reduced over the first 3×10^8 years of life by the mass loss (stellar wind) flowing out through the long arms of the extended magnetic field of the star. There is no reason to think that the magnetic field penetrates through the core of the star, so the process might well leave the core with the original spin. The point of this speculation is that a rapidly spinning core would be slightly flattened (oblate) by the centrifugal force, and the gravitational field of the core would be correspondingly nonspherical. It is readily shown that a consequence would be a precession of the perihelion of Mercury produced by the core alone. So, the error in the Newtonian theory would be less than the 43 arc seconds per century, and the unique prediction of general relativity would be in error, agreeing with the observational result only by chance coincidence. The experimental test of this idea lay in searching for the associated very slight oblateness of the surface of the Sun. Dicke developed an optical apparatus for scanning around the rim of the Sun to see whether it might be slightly oblate. The rim of the Sun is distorted by prominences, faculae, the chromosphere, etc. However, by scanning just inside the limb of the Sun, Dicke devised ingenious ways of reducing the contributions of these effects, and, in the end, there has been no conclusive demonstration of any interesting deviation from a purely circular solar disk. What is more, recent probing of the rotation of the Sun by helioseismology – on which more will be said later – shows no rapidly spinning core. The verdict seems to be that the Sun is round, general relativity is precisely correct, and there is no significant presence of a scalar gravitational field in addition to the tensor field of general relativity.

Note, then, that general relativity has become the theoretical basis for understanding the dynamics of the expanding universe, with recent observational indications that the expansion may be accelerating and the bothersome cosmological constant may not be identically zero.

2. Internal structure

Now if the gravitational field of the Sun and the rotation rate of the core have played a central role in establishing the correct formulation of gravity and mechanics, what can the structure and behaviour of the solar interior tell us about its physics? The development of the kinetic theory of gases and the recognition of the critical temperature of liquids and solids in the second half of the 19th century led to the realization of the entirely atomic gaseous composition of the Sun, too hot throughout the interior for any chemical bonding to form molecules. Spectroscopy and thermodynamics established the surface temperature at 5600 K. The virial theorem of mechanics made it clear that the interior must be very much hotter ($\sim 10^7$ K) in order to maintain the radius (7×10^5 km) in opposition to the immense gravity (28 times the gravitational acceleration of 9.8 m/sec^2 at the surface of Earth). Lane in 1869 and Emden in 1907 constructed simple mathematical models of the interior of the Sun by assuming that the temperature varies as some power of the density, $T \sim \rho^{\gamma-1}$, where $\gamma (> 1)$ is a constant. Thus, for instance, if a purely monatomic gas were to mix adiabatically throughout the interior, γ would be 5/3. The essential point is that the mathematical model could be made to fit the mass and radius of the Sun by suitable choice of mean atomic weight and γ, and one could see how the kinetic theory of gases and Newtonian gravitation provide a satisfactory representation of the Sun. To do more required some knowledge of the physics of the outward radiative transfer of heat within the Sun[2].

An obvious question, then, was the heat source that maintains the temperature of the Sun. Chemical combustion is entirely inadequate, providing the energy of the Sun for only a couple of thousand years. Helmholtz in 1854, and later Kelvin, pointed out that the gravitational energy of the Sun is more than a thousand times greater than any hypothetical chemical energy. The concept is quite simple. The surface of the Sun is hot, so that it cannot avoid radiating energy away into space. So the internal thermal energy would decline except for the fact that gravity would cause the Sun to shrink, compressing the gas until it is even hotter than before in order to oppose the increased gravity of the shrinking Sun. So the temperature within, and at the surface, increases as the radius of the Sun declines. To put it in other words, the Sun is stable against radial disturbances. An inward kick merely causes the Sun to contract and then rebound. So the net result of the continuing radiation from the surface of the Sun would be slow contraction over several million years, with the gravitational force compressing and heating the gas to even higher temperatures. The Sun would grow brighter with the passage of time as a consequence of the temperature increase.

The rate of contraction of the Sun is easily computed to be about 50 m/year and is entirely undetectable in the brief span of human science. The Sun would gradually increase in brightness over a couple of million years. It is interesting to note that Kelvin took this scenario so seriously that he rejected Darwin's proposal of biological evolution on the grounds that there simply was not enough time for evolution to take place. Fortunately the geologists stepped in with clear evidence that – Darwin or not – the rock structures found at the surface of Earth require 10^8 to 10^9 years for their formation, and there was evidently plenty of time for biological evolution. Thus the age of Earth vitiated Kelvin's gravitational contraction as the principal source of energy for the Sun.

With the recognition by Einstein of the equivalence of matter and energy, thinking turned to the annihilation of mass by some unknown process as the sustaining source for the Sun[2]. With the luminosity of 4×10^{33} ergs/sec, this means that the mass of the Sun is declining at the rate of 4×10^{12} g/sec (4 million tons/sec). Ultimately, Bethe and others[3–5] supplied the answer based on the newly founded nuclear physics, pointing out both the proton–proton chain and the carbon cycle. Both processes fuse four hydrogen nuclei into one helium nucleus, converting about one per cent of the mass into energy. The proton–proton chain is the more effective of the two in the Sun, where the central density is of the order of 10^2 g/cm^3 and the temperature is 1.5×10^7 K. Hydrogen is converted into helium at the rate of 4×10^{14} g/sec (400 m tons/sec).

Now the present age of the Sun is inferred from the assumption that the Sun and Earth were formed more or less simultaneously, and the uranium and lead isotope ratios in the crust of Earth indicate an age of 4.6×10^9 years. In that span of time, approximately 6×10^{31} g of hydrogen, representing 3 per cent of the mass of the Sun, have been converted to helium, with a total loss in solar mass of 6×10^{29} g.

The production of helium in the central core of the Sun increases the mean atomic weight, of course, and the result is a slow contraction of the core to increase the temperature to support the core in opposition to gravity. The helium also has the effect of diluting the hydrogen so that the core contracts until the density and temperature increase to maintain the thermonuclear energy supply. Thus the Sun is now smaller, hotter, and approximately 30 per cent brighter than it was in early times. The fact that the Sun was substantially fainter 4×10^9 years ago raises interesting questions about the temperate climate of Earth, and even Mars, at that time.

3. Composition of the Sun

Before going into helioseismology and neutrino emission, consider the knowledge of the interior of the Sun about a hundred years ago. Spectroscopy showed a spectrum dominated by the lines of such elements as carbon, calcium, sodium, silicon, iron, magnesium, etc., suggesting that the Sun was composed largely of the vapours of these substances. The immediate problem was that such large atomic weights required a much hotter Sun than the mathematical models could accommodate to maintain the Sun against its own gravity. Hydrogen and helium (which was discovered spectroscopically on the Sun before it was known in the laboratory), suggested by the atomic weights needed for the mathematical models, were relatively inconspicuous in the solar spectrum, and in any case were too transparent at 5600 K to account for the opaque surface layer of the Sun. The fuzziness of the visible surface of the Sun in white light is limited to something of the order of 100 km at the center of the disk.

To make a long story short, the dilemma was resolved by the negative hydrogen ion—a hydrogen atom with an additional electron orbiting about it. Hans Bethe first calculated the existence of this atomic structure, pointing out in 1929 that the electron is attracted to the electrically neutral hydrogen atom because the presence of the external electron attracts the positively charged nucleus and repels the negative electron cloud. Thus, the otherwise spherical hydrogen atom is slightly distorted with a small net positive charge in the end pointing toward the external electron.

Ten years later, Wildt[6] pointed out the astrophysical implications of the negative hydrogen ion. The loosely bound external electron is nicely tuned to absorbing and re-radiating light, so it serves very well at the 5600 K temperature of the visible surface of the Sun in impeding the passage of light and providing a relatively sharp visible surface. Chandrasekhar[7] and others undertook the difficult task of precise calculations of the properties of the negative hydrogen ion.

Spectroscopic observation of the 'red flames' or chromosphere of the Sun that peek around the limb of the Moon during an eclipse indicated that hydrogen is the most abundant element in the Sun. Hydrogen shows clearly in the chromosphere because the temperatures are somewhat higher (6000–8000 K) than at the visible surface. The 5600 K at the surface only weakly excites the sturdy hydrogen atom, where the hydrogen is able to hang on to that extra electron to form the negative ion. The chromosphere is better suited to exciting the hydrogen atom, but, of course, is so hot as to knock the negative hydrogen ion to pieces. So the dilemma was resolved! The Sun is mostly hydrogen, with about one in ten atoms being helium. The heavier elements are present only at the one per cent level, or less, and their weaker electron structures are strongly excited by the 5600 K at the surface so that they dominate the line spectrum there.

With some knowledge of the composition of the Sun, the next step in working out the structure of the interior requires knowledge of the impediment of the gas to the passage of electromagnetic radiation, dominated by soft X-rays in the core where $T \sim 1.5 \times 10^7$ K, and by visible light at the surface where $T \sim 5600$ K. There is an ultraviolet domain between. The impediment is called the *opacity* and its calculation requires computing the absorption and re-radiation by each of the atomic constituents. The high temperature in the deep interior of the Sun means that the atoms are highly ionized, with only the heavier elements, e.g. Ca, Si, Fe, etc. able to hang on to one or two of their innermost electrons. These few bound electrons make a major contribution to the opacity so essentially all atomic species have to be treated in their several states of ionization.

One can begin to see the immensity of the task[2]: One needs precise detailed models of the solar atmosphere in order to determine the relative abundances of the elements at the visible surface from spectroscopic observations. The assumption is made that the relative abundances of the elements is the same in the interior as at the surface. Then the enormous calculation begins computing the probability of each number of electrons knocked off each different element at arbitrary temperature and density, and then computing the absorption of radiation by the electrons still attached. From this a table of opacity as a function of temperature and density can be constructed. Then finally, one can address the problem of computing inward from the visible surface where the temperature and density are known. The temperature must increase inward sufficiently rapidly to provide the observed outflow of heat (4×10^{33} ergs/sec). At the same time the density must increase inward sufficiently rapidly that the gas pressure (the product of temperature and density) is sufficient to support the weight of the overlying layers of gas against the gravitational field of all the matter below. For this reason, the procedure is usually reversed, starting with an assumed temperature ($\sim 1.5 \times 10^7$ K) and density (~ 100 g/cm^3) at the center and calculating outward. The local rate of thermonuclear energy production has to be worked out too, of course, in order to know the outflow of energy at each radius. When the calculation arrives at the surface, where the temperature and density essentially vanish, the total mass and radius of the theoretical model are obtained. The calculation is repeated for different central temperature and density until the result matches the Sun. Then, once the Sun is properly modelled, the calculations can be applied to other stars where the radius is not precisely known, although the masses can be determined in double-star systems. It is interesting to note, then, that the deep interior of the Sun turns out to be stably stratified against vertical mixing. That is to say, the central core is hotter than the overlying layers, but not enough hotter that it can exchange places. Any upward displacement of gas from the core provides expansion and cooling to such a degree that the uplifted gas is cooler than the ambient gas, so that the uplifted gas is denser than its surroundings and relaxes back into the core.

This is all based on well-known principles of physics, but the computation of opacities, with hundreds of different ions, is so complex and tedious that estimates are introduced in place of detailed computations for many classes of ions. The problem has been taken up in weapons laboratories where the properties of nuclear bomb explosions are explored theoretically, using many of the same opacities. The tables of opacities have been improved for this purpose, allowing more precise calculation of the interior of the Sun. A number of refinements have been introduced, such as the accumulation of helium throughout the central core as the hydrogen burning progresses, and the gravitational settling of the heavier ions relative to the lighter constituents with the passage of time. The result is a detailed quantitative model of the internal structure of the Sun.

Then comes the ultimate question: Is there some way to check this sophisticated theoretical model of the interior to be sure that it is correct? Are the abundances of the elements really the same as at the surface? Is there really no vertical mixing of the elements in the core? Is the Sun really as old, or as young, as the Earth?

4. Probing the interior

The first test for the theoretical model of the solar interior was based on the emission of neutrinos from the thermonuclear reactions in the core. Neutrinos pass so freely through matter that they easily escape from the core, being the only messengers coming directly from the core to the outside world. Needless to say, their free passage through matter makes them extremely difficult to detect – difficult but not impossible[8,9]. With six-hundred tons of cleaning fluid in a tank deep in the Homestake Mine in South Dakota (to get away from the spurious effects produced by cosmic rays) Ray Davis looked for neutrinos above 0.8 MeV reacting with the chlorine in the cleaning fluid to produce the radioactive isotope ^{40}A. The argon atoms are radioactive with a half-life of about a month, and are swept out of the cleaning fluid about once a month to be detected and counted by their radioactive decay. To make a long story short, the theoretical models of the solar interior forty years ago when the planning of the experiment was initiated, suggested one or two argon atoms per day. In fact Davis found nothing beyond statistical fluctuations in the background count rate. A careful re-evaluation and refinement of the theoretical model, leading to a small downward readjustment of the central temperature of the Sun, drastically reduced the expected neutrino detection rate, to something of the order of five per month. The continuing accumulation of data in the Homestake detector gradually reduced the statistical uncertainties, to where it began to appear that there really were neutrinos from the Sun, but only about a third of the expected number[10,11]. The question was whether the theoretical model of the Sun was in error, or was there something about the physics of neutrinos that was not properly understood? In particular, neutrinos have conventionally been assumed to have no rest mass, in the same way that a photon of light has no rest mass. That is to say, a neutrino travels through free space at the speed of light and experiences no passage of time. However, it is not impossible that a neutrino has a rest mass, so that it experiences the passage of time. If so, it would open up the possibility that the electron neutrinos emitted from the core of the Sun oscillate through the *mu*-neutrino state and *tau* neutrino state during their passage to Earth. In that way the electron neutrinos would spend only one-third of their time in the electron–neutrino state to which the Homestake detector is sensitive. The result would be the detection of only one third of the expected number of neutrinos.

This dilemma has been cleared up in favour of unknown neutrino physics, because of the precise probing of the interior of the Sun through helioseismology. It was first noted by Leighton that the surface of the Sun is continually agitated by fluctuations with periods of the general order of 5 min. Imagine a pan of water sitting in a metal sink with some such machinery as a garbage grinder running immediately below. The vibrations set up a pattern of small-scale waves on the surface of the water. Roger Ulrich[12] and Leibacher and Stein[13] recognized that the oscillations in the Sun represent sound-waves trapped between the surface of the Sun and a refractive turn-around far below the surface. The Sun rings like a bell, but at a thousand different frequencies all at once. The essential point is that the period of each mode of oscillation is just the sound-transit time along the path of the sound wave down and back up through the interior. Each acoustic mode represents a sound wave travelling on a different path down into the Sun, around, and back up to the surface. Some paths go deep, some are only shallow, etc. The theoretical model of the solar interior provides the speed of sound as a function of depth from which one can calculate the path of each acoustic wave mode, and the transit time along that path for each acoustic mode. The transit time determines the period of the oscillation at the surface of the Sun. The calculated periods are then compared to the observed periods for several hundred different modes, sampling different depths. It is a precision test of the theoretical model, and it is gratifying to find that, when all the refinements of the theoretical model are included, the periods provided by the theoretical model agree closely with the observed periods, indicating that the speed of sound in the theoretical model nowhere differs by more than one-part in five-hundred from the actual speed of sound—approximately the expected observational error[11]. It appears then that the theoretical model of the interior of the Sun is properly constructed and there are no anomalous abundances of elements in deeper layers of the Sun. This is a major triumph for theoretical physics.

Turning again to the low level of neutrino emission from the Sun, the evident accuracy of the theoretical model of the interior leaves only unknown neutrino physics as the explanation for the discrepancy[11]. This challenge has generated a vigorous response among physicists. The first step was to build a neutrino-detecting system using gallium instead of chlorine (in both Italy and the former Soviet Union) to detect neutrinos down to 0.2 MeV, thereby picking up the neutrinos emitted in the initial p–p reaction of the proton chain. The huge water–Cerenkov detector, Kamiokande, in Japan, was also applied to the task, providing both the energy and direction of the incoming neutrino. The data is from these three additional projects, and they all detect neutrinos from the Sun, but only at about a third or half of the predicted number, more or less along the same lines as the Homestake detector. The next generation of neutrino detectors is coming on line, designed to give the energy and direction of each incoming solar neutrino at substantial count rates of ten or more per day (Super Kamiokande in Japan; the heavy-water Sudbury Neutrino Observatory in Ontario (Canada), and Borexino (Italy)). In the meantime, Super Kamiokande has shown that neutrinos do, in fact, have a nonvanishing rest mass, based on measurements of the difference in the up-and-down fluxes of the neutrinos produced by cosmic rays colliding with the terrestrial atmosphere. The essential point is that the downward neutrinos are fresh from their creation in the atmosphere overhead, while the upward moving neutrinos have passed through the solid Earth in a time of the order of 30 milliseconds, allowing time for conversion to neutrino states not detected by Super Kamiokande.

5. Convection and magnetic fields

There is a branch of classical physics that is challenged to come up with new concepts, by the seemingly innocent fact that the theoretical model of the interior of the Sun provides an outer region of convective turnover, extending up to the visible surface of the Sun from a depth of 2×10^5 km (solar radius = 7×10^5 km)[14]. The continual turnover of the gas arises because the radiative transfer of heat deep in the Sun becomes less effective as the temperature diminishes outward, with the result that it cannot handle the heat transport when the temperature falls below about 2×10^6 K at the depth of 2×10^5 km. The outward heat flow is 4×10^{33} erg/s, and to transport so much heat by radiation the temperature would have to decline outward so rapidly that the cooler gas above becomes too dense, and the hotter gas below becomes too tenuous for stability. The hot and cold gases prefer to exchange places, providing convective turnover just like the rolling boil of the water in a pot on a hot stove. The resulting vigorous vertical mixing of the gas takes over the heat transport to the surface.

The small effect of the convection on the overall theoretical model of the solar interior is easily handled by approximate methods known from hydrodynamics as the mixing length theory, and, as already noted, there seems to be no problem there. The new physics arises because the gas within the Sun is so hot as to be ionized, providing free electrons so that the gas is an excellent conductor of electricity – as good as cold copper in the central regions. The high electrical conductivity over the broad Sun means that there can be no significant electric field in the local frame of reference of the moving fluid, because any attempt to initiate an electric field would be met by a rush of free electrons, neutralizing the attempt. It follows that any magnetic field present in the gas is carried along bodily in the swirling convection, always moving in the frame of reference in which there is no electric field. The magnetic field is swirled, stretched, and deformed just like a wisp of smoke. Only when the magnetic field becomes so strong that it can physically stop the convection does the mixing, stretching, and intensifying of the field cease.

The effects that arise from this simple magnetic transport property of hot ionized gas, or plasma, are legion, and involve hitherto unfamiliar combinations of hydrodynamics, magnetohydrodynamics, and local radiative transfer. First of all, there is the convection itself, extending from where the plasma density is 0.2 g/cm^3 at the base of the convective zone up to the visible surface where the plasma density is 0.2×10^{-6} g/cm^3. An understanding of convection in an atmosphere with such strong vertical stratification is only beginning to be developed. Numerical simulations are the principal tool for exploring the subject, but, computers are still some way from being able to handle so much stratification. The convection has a number of characteristics quite unlike convection in a pot of water, where the fluid has essentially uniform density. For instance, numerical simulations have shown that there are downward plunging clumps of cold dense gases. The nonuniform rotation of the Sun is presumed to be a direct result of the convection, but it has not yet been possible to simulate the convection with sufficient accuracy and detail to show how this works. As another example, the formation of a sunspot represents a systematic concentration of magnetic field driven by the convection in opposition to the enormous pressure of the magnetic field, and once again the convective mechanism is not understood.

The explosive flare phenomenon is an example of magnetohydrodynamic interaction where at least the general principles seem to be in hand. Flares are observed on all scales from the largest (~ 10^{32} ergs over dimensions of 10^4 km) down to the limit of detection (~ 10^{25} ergs over 10^2–10^3 km), rapidly converting magnetic free energy into hot plasma and fast particles. The basic effect appears to be rapid dissipation and reconnection of nonparallel magnetic fields. The discovery of this peculiar aspect of classical physics was motivated by the otherwise inexplicable explosive conversion of magnetic energy required to explain the flare[15,16]. That is to say, the physicist is lured onward by the mysteries presented by Nature, and the observations provide some hint as to the nature of the unknown physical effects.

Rapid reconnection involves such diverse phenomena as plasma turbulence in the small and the Petschek effect in the large, and the subject is active today, with attention directed to the various forms the dynamics can take in three dimensions and to the acceleration of ions and electrons to very high energies in the central regions of the dissipation. The ubiquitous nature of rapid reconnection in the astronomical universe is demonstrated observationally by the widespread astronomical appearance of million degree tenuous plasmas and fast particles, and is to be understood in terms of the spontaneous appearance of discontinuities (intense current sheets) in any magnetic field embedded in a plasma undergoing slow continuous deformation[17,18]. The effect arises from the nature of the Maxwell stress tensor for the magnetic field. Each surface of discontinuity, or current sheet, becomes a site for resistive instabilities and rapid reconnection, i.e. explosive dissipation of magnetic free energy. It appears that this general theoretical property of the magnetic field is the major heat source responsible for the X-ray emitting corona of the Sun, on which more will be said later.

This brings us to the fact that the outer atmosphere of the Sun – the corona, conspicuous when the dazzling disk of the Sun is obscured by the Moon during an eclipse – is heated to temperatures in excess of a million degrees. So high a temperature was suggested a hundred years ago by the great outward extension of the corona in opposition to the powerful gravitational field of the Sun (28 times the acceleration of gravity at the surface of Earth). Then in the 1930s the temperature was confirmed by some clever experiments in the terrestrial spectroscopy laboratory, showing that the observed spectral lines are from 10, 11, and more times-ionized iron, silicon, calcium, etc., occurring only at million degree temperatures[19–21].

The corona is so tenuous (typically 10^8 atoms/cm^3 near the Sun) that it cools only relatively slowly by radiation, while it has an enormous thermal conductivity as a consequence of the high temperature and the associated 10^4 km/sec thermal velocities of the free electrons. Thus it is not surprising that the million degree temperature extends far out into space. The corona is strongly bound by gravity near the Sun, where the mean thermal energy is only about a tenth of the energy necessary to escape from the Sun. The outer regions, far from the Sun, are not strongly bound and escape into space. The surprise was that Newton's equation of motion showed that there is no static equilibrium for such an atmosphere, the only steady state being gradual outward acceleration, from negligible velocity (~ 1 km/sec) near the Sun to supersonic velocity (300–1000 km/sec) at large distance. This is the origin of the solar wind, which drags the weaker magnetic fields of the Sun along with it, thereby filling all of interplanetary space with an outward sweeping spiral (because of the rotation of the Sun) magnetic field[22]. The outward sweeping wind and field push back the galactic cosmic rays to some degree, impact and agitate the magnetic fields of Earth, Jupiter, Saturn, etc., and generally determine the dynamical state of space throughout the solar system[23]. The outstanding question remaining is the heat source that creates the million degree temperatures around the Sun.

6. Magnetic fields of the Sun

Ordinarily, in the terrestrial laboratory, we do not think of magnetic fields in association with gases; we think of iron magnets and coils of copper wire carrying electric currents (electromagnets). But in fact, as already noted, a gas sufficiently hot as to be fully ionized and an excellent conductor of electricity over the large dimensions appropriate to the Sun carries with it whatever magnetic fields happen to be present, on a more or less permanent basis. Rapid reconnection at incipient discontinuities is the one scheme that can quickly dissipate the magnetic field, by the simple expedient of creating very small scales in the structure of the field. But this rapid dissipation is effective only in the tenuous outer atmosphere of the Sun, and it is not obvious that it occurs in the tumbling convection below the surface of the Sun, where the gas is so dense as to respond only sluggishly to the magnetic forces.

Magnetic fields were first established on the Sun by George Ellery Hale[24] when he observed the Zeeman splitting of some of the spectral lines in sunspots. The splitting indicated magnetic fields of 2000–3000 G in the dark central umbra of the spot. That is a very strong field, comparable to what can be produced in a strong electromagnet. Hale went on to point out that the magnetic field in the leading and following spots of each bipolar sunspot group had opposite sign, suggesting that the field emerges from one, arches over and returns back into the Sun in the other. He noted, too, that magnetic fields have opposite directions in the northern and southern hemispheres, and the whole magnetic system reverses with each successive 11-year sunspot cycle, which is now often referred to as the magnetic cycle since it is driven by the generation of magnetic field deep in the convective zone.

Following World War II, the advent of electronics made it possible to develop a much more sensitive magnetograph, which soon detected magnetic fields of other stars and showed that there is a general background dipole magnetic field in the Sun of about 10 G, extending in at the north pole and out at the south pole, or vice versa in the next 11-year period[25]. The general field reverses near the maximum of the sunspot cycle when most of the sunspots are popping up within about 15° of the solar equator. The Babcocks also found that the active regions, in which the sunspots and large flares occur, lie in the midst of extended bipolar regions of ~ 100 G. The bipolar character of these regions of magnetic activity indicates that the magnetic fields are part of a general intense east–west magnetic field somewhere deep in the convective zone. The individual bipolar active region is created by the upward bulging of a segment of that east–west field, the bulge having the form Ω of the capital omega.

The first question is obviously the origin of the magnetic fields, for which the answer seems to be that the nonuniform rotation of the Sun (for instance, the equatorial surface of the Sun has a 25-day rotation period, while the polar regions rotate in approximately 30 days) continually shears and stretches out the dipole component of the magnetic field into an east–west field, while the cyclonic rotation of the tumbling convection raises and rotates Ω loops in the east–west field to reinforce the dipole field[26–28].

Why, then, are sunspots formed in the otherwise 100 G surface regions of bipolar field? There one can only say that 'we do not know'. The magnetic field somehow interacts with the convection and the convection somehow interacts with the magnetic field to compress the field into the 2000–3000 G, that is observed. This all takes place in opposition to the enormous pressure of the 2000–3000 G field.

It is observed that the tenuous gas trapped in the strong (100 G) bipolar fields of the active regions is heated to temperatures of $2–5 \times 10^6$ K, and along some bundles of field lines the density becomes so high (10^9–10^{10} atoms/cm^3) as to produce strong thermal emission of X-rays (10^7 ergs/cm^2 sec). In contrast, the broad regions of weak field (5–10 G) are heated to temperatures of 1.5×10^6 K and more, with densities limited to 10^8 atoms/cm^3 by the free expansion of the gas to form the solar wind, as already noted. It appears at the present time that this expanding corona is heated largely by the microflares (10^{25}–10^{28} ergs) among the small magnetic elements that appear at the surface of the Sun, while the dense X-ray corona is heated by even smaller flares (nanoflares, below the limit of detection by present instruments) arising in the spontaneous discontinuities created in the 100 G bipolar fields by the continual intermixing of the footpoints of the field at the convecting surface of the Sun[18].

Speaking of the small magnetic elements brings us to further subtleties in the mysterious behaviour of the Sun. About thirty years ago it became clear from quantitative observational studies that the magnetic fields of the Sun do not form a continuum at the surface of the Sun, but instead are made up of widely separated tiny concentrated magnetic flux bundles or magnetic fibrils of 1000–2000 G with diameters of the general order of 100 km. Each separate fibril is held in the grip of the surrounding gas, for otherwise it would expand and disperse. The typical observed mean field of 10 G is merely a measure of the spacing of the many unresolved individual magnetic fibrils. The 100 G regions have their fibrils more closely spaced. Only recently has it been possible to detect the individual fibrils and it is not possible to resolve their internal structure nor to study their interactions with ground-based telescopes because the atmosphere above the telescope limits the resolution to ~ 300 km even under the best seeing conditions.

One asks why the field is in this peculiar state with so much 'unnecessary' free energy. New fibrils continually bulge upward through the surface, forming small Ω loops and jostling against each other to provide the microflaring that seems to be the main energy source for the solar wind. These small-scale fibrils and bipoles appear over almost the entire surface of the Sun. These background fibrils show only modest variation with the 11-year cycle, suggesting a different origin from the main fibril fields of the active regions.

A critical review of the standard explanation for generating the magnetic fields of the Sun, already mentioned, offers no enlightenment, and, in fact, turns up another serious puzzle. For the fact is that the generation of magnetic field by the cyclonic convection and non-uniform rotation of the Sun requires that the magnetic field diffuse across the surface of the Sun and the depth of the convective zone during the 11-year magnetic cycle. No adequate diffusion mechanism is known. We used to think that the turbulent convection mixes the magnetic field over these dimensions, the way turbulence mixes a puff of smoke throughout a room. But it is now clear that the mean magnetic field in the deep convective zone is at least 10^3 G, and much too strong to submit to the 'indignity' of turbulent mixing. It may be that the answer to the dilemma lies in the individual fibril being the basic magnetic entity, rather than the mean fields usually employed in calculating the generation of magnetic field. The fibrils are capable of rapid reconnection where they meet and may be transported more freely. But, all this has to be worked out quantitatively before any claim to understanding can be made.

It is clear that the first step in studying the fibril nature of the magnetic field is to develop and construct a ground-based telescope that can resolve and study the detailed properties of the magnetic fibrils, as the principal players in the magnetic activity of the Sun. They appear to be the microscopic architects of sunspots, flares, coronal heating and the solar wind, and the generation of magnetic field itself, and yet we cannot see them clearly from Earth. The development of adaptive optics to correct for the blurring by the atmosphere above the telescope has now progressed to the point that the necessary resolution of 0.1″ (75 km), or better, should be possible. High-spectral resolution combined with the necessary rapid-observing cadence (~ 10 sec) and the high-spatial resolution require a large aperture (~ 4 m) to gather enough photons. It is an essential step if we are to advance the physics of the active Sun. In fact the implications of the variable magnetic activity of the Sun, the associated varying brightness of the Sun, and the resulting climatic effects here at Earth, together with the implications for the activity of all stars and the new physics to be learned, place the successful construction of such a solar telescope at the highest priority, which brings us to the last section of this brief review.

7. The terrestrial challenge

NASA began monitoring the brightness of sunlight with absolute radiometers on orbiting spacecraft in 1978, with the startling discovery that the brightness varies by as much as 0.15 per cent with the 11-year variation of sunspots, flares, and general magnetic activity of the Sun. More recent monitoring of other solar-type stars shows that they do much the same, with one such star, ominously, showing a decline in brightness of 0.4 per cent over only six years as its activity tumbled to low levels[29]. Jack Eddy[30] emphasized some years ago that the Sun was almost entirely without activity over the seventy-year period of 1645 to 1715, called the Maunder Minimum after its discoverer at the end of the 19th century. With modern ^{14}C-production data, Eddy went on to show that the Sun went through another extended inactive period during the 15th century and a prolonged state of hyperactivity during the 12th century. Zhang *et al.*[29] estimated that the brightness of sunlight was depressed by something of the order of 0.4 per cent during the Maunder Minimum and probably enhanced above normal by a comparable amount during the 12th century. Then Eddy noted that the mean annual temperature in the Northern Temperate Zone varied up and down 1–2°C, while tracking these variations in solar activity. The close tracking of climate with solar activity has been investigated in detail since that time and proves to be much closer than Eddy could have imagined with the data available at that time. Historically, the extreme cold periods had devastating consequences for agriculture in northern Europe and China, and the warm periods had devastating consequences around the periphery of desert regions, e.g. what is now southwestern United States.

The bottom line is that the great physics laboratory in the sky not only extends our opportunities to study physics, but some of its more mysterious demonstrations have profound implications for the human population of Earth. In particular, the Sun has become substantially more active during the 20th century, and presumably brighter on the average by as much as 0.1 per cent. The general warming of the climate from 1900 to 1950 would appear to be a consequence of this phenomenon. Since that time the climate picture has been complicated by the substantial increase in carbon dioxide in the atmosphere and the warmer sea water temperatures which discourage the absorption of the carbon dioxide into the oceans. It is a problem that needs to be thoroughly investigated so that we can have some idea of how to respond to these changes.

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MEETINGS/SYMPOSIA/SEMINARS

International Conference on Microbial Biotechnology, Trade and Public Policy

Date: 15–17 July 2000
Place: Hyderabad, India

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National Conference on Recent Trends in Biotechnology

Date: 3–5 February 2000
Place: Amravati, India

The conference will consist of invited lectures and paper presentations in the following areas: Molecular biology and genetic engineering; Plant tissue culture and plant biotechnology; Fermentation biology and biochemical engineering; Cell biology and microbial biotechnology; Bioinformatics and Analytical techniques; Immunology and animal biotechnology.

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National Conference on Aquaculture and Steps to Maintain High Production

Date: 21–22 January 2000
Place: Calcutta, India

Themes include: Aquaculture biotechnology and fish genetics; Fresh water aquaculture; Coastal aquaculture; Protection of aquatic biodiversity and environmental impacts; Wetland management and waste recycling; Post-harvest technology; Fisheries extension education and role of NGOs.

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Entomocongress 2000: Perspectives for the New Millennium

Date: 5–8 November 2000
Place: Thiruvananthapuram, India

Themes include: Concepts and strategies of insect pest management; Physiology and molecular biology; Ecology; behaviour and insect-host interactions; Taxonomy; biodiversity and evolution.

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