REFLECTIONS ON MACROPHYSICS AND THE SUN

(Special Historical Review)

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1. Introduction

The terrestrial laboratory has supplied the experimental facts from which the basic mathematical laws of thermodynamics, electromagnetic fields, quantum mechanics, and particle physics are derived. With supplementary observations of planetary motions, the laboratory has provided the mathematical laws of mechanics and gravitation. Turning to the astronomical universe we find a staggering variety of exotic macrophysical effects that cannot be set up on the small scale of the terrestrial laboratory, but which we presume are all consistent with the basic physical laws of the laboratory. The challenge is to discover the proper connection of the macrophysical phenomena to the laboratory mathematical laws, and that can be accomplished only where observations provide enough quantitative detail to define the problem.

Note, then, that when we venture out of the physics laboratory to examine the macroscopic astronomical universe, the striking feature, which we generally take for granted, is the evident universal nature of the laboratory physics. The physics appears to be the same in all places, at all times, and in all inertial frames of reference in the Universe. Thus the electromagnetic emission spectra of stars and distant galaxies indicate the familiar electrodynamics and quantum mechanics of the laboratory atoms. Stellar atmospheres exhibit universal characteristics, implying the universal properties of the elements, gravity, electromagnetic propagation, and nuclear physics in the stellar interiors and atmospheres.

Remote observations of the stars and galaxies, and particularly of the Sun, together with *in situ* studies of the solar system with instruments carried on spacecraft, must be our guide to macrophysics. The task of the physicist is to initiate and interpret the observations, constructing theoretical understanding in terms of the mathematical laws of physics once the observations have suitably constrained and defined the problem. It is essential in these exuberant times to pay critical attention to both the observational constraints and to the basic mathematical laws, with a clear sense of what is solid theory and what is only unsupported speculation. This seeming platitude is offered here without jest, because at the present time there are

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'theories' – scenarios sometimes quite detailed – seriously and often passionately held, for almost every exotic astronomical object that is not resolved in the telescope. In contrast, the one star that can be properly resolved – the pedestrian Sun (cf., Goldberg, 1953; Strömgren, 1953) – exhibits a variety of phenomena that defy contemporary theoretical understanding. We need look no farther than the sunspot, or the intensely filamentary structure of the photospheric magnetic field, or the spicules, or the origin of the small magnetic bipoles that continually emerge in the supergranules, or the heat source that maintains the expanding gas in the coronal hole, or the effective magnetic diffusion that is so essential for understanding the solar dynamo, or the peculiar internal rotation inferred from helioseismology, or the variation of solar brightness with the level of solar activity, to name a few of the more obvious mysterious macrophysical phenomena exhibited by the Sun. Indeed the Sun and the solar system have been the basis for the many historical triumphs of macrophysics, from the Newtonian mechanics of the orbiting planets to the interior and atmospheric structure of the Sun and other stars, and to Einstein's serendipitous construction of the relativistic theory of gravitation.

Historically the Sun has served as the prototype for all stars, providing a precisely measured mass, radius, surface temperature, luminosity, atomic abundances, center to limb variations, etc. In particular, the Sun is the only star outside globular clusters for which we think we know the precise age. Helioseismology has largely verified the basic theoretical static structure of the solar interior. The present intensive neutrino observations, originally intended to probe the interior, are now pursuing a peculiar discrepancy between the predicted and the actual rate of detection of solar neutrinos in the terrestrial laboratory. It appears from the measurements to date that the discrepancy may arise from unknown neutrino physics rather than from some unusual condition in the thermonuclear core of the Sun. If that ultimately proves to be the case, then the static Sun is presumably properly understood, allowing its long-term evolution to be deduced and substantiating the application of the theory of stellar interiors to other stars. So it appears that the macrophysics of the interior of stars on the Main Sequence may be well in hand, although the final word is not in on the neutrinos, to which we return later.

The feature of the Sun that is presently of greatest interest arises from the fact that the Sun is much more than a stable (but see Eddington, 1926, pp. 303–306 and Cowling, 1934) self-gravitating, thermonuclear powered object, for observation shows a remarkable repertoire of magnetic features emerging through the surface, creating a spectacular variety of suprathermal effects in the atmosphere above. That is to say, the Sun is superficially an extraordinarily active object, for all the profound internal gravitational stability. The activity is evidently a consequence of large-scale magnetic effects – macrophysics – that mostly cannot be set up in the terrestrial laboratory. We have no reason to doubt that the magnetic activity of the Sun is in conformity with the equations of Newton and Maxwell. On the other hand, there are many aspects of the activity that we do not understand, e.g., the fibril state of the photospheric magnetic fields and their subsurface origin on both small and large scales. It follows that there are large-scale manifestations of Newton and Maxwell yet to be discovered beyond the many successful advances over the past century. So this article is written in the spirit of a prologue to the fascinating macrophysics still to be accomplished.

One last comment should be made in preparation for reviewing some of the triumphs of macrophysics accomplished by close study of the Sun over the last century. The comment is that in contrast with the popularity of one casual 'theory' or another for exotic astronomical objects, there is a striking reluctance, which we might call intellectual inertia, toward accepting new macrophysical concepts when they arise from basic physical principles and observational facts. One example suffices to illustrate this psychological or sociological phenomenon. We choose the non-LTE controversy of forty and fifty years ago. By the early fifties it was clear that the chromospheric hydrogen and helium spectra could not both be fitted by theoretical considerations based on local thermodynamic equilibrium, in which detailed balance provides the Boltzman distribution $\exp(-E/kT)$ over energy E. This was hardly surprising because in the chromosphere the kinetic temperature of the electrons exceeds the color temperature of the radiation field, which in turn exceeds the black body temperature of the radiation density. So there is no unique temperature T and no reason to expect detailed balance among energy levels. A quantity of earlier theoretical work on stellar spectra was called into question and it was clear that many theoretical problems, e.g., chromospheric spectra, would be difficult to solve because the population of energy states would have to be deduced by treating the rate equations for all the important emitting states. The new concept of non-LTE was firmly denied for years by many prominent workers in the field, who therefore contributed nothing further to the analysis of chromospheric spectra. The episode is not atypical of scientific progress in general.

So the sociology of scientific advance is a complicated and fascinating subject. It is something that should be viewed in perspective by all of us practicing scientists, whose collective character is the basis for the sociology. It is ourselves that we see in the mirror of history, and if the reflected countenance is sometimes frowning, it is our own brow that may be wrinkled.

2. General Considerations

We begin with a review of some of the well-known, but little noted, questions and facts about the Sun. For instance, there is the traditional question of why the Sun has a mass $M_\odot$ of 2×10^{33} g and why the range of masses of all stars is approximately 10^{-1}–10^2 $M_\odot$. The answer to the first part of the question seems to be that the yellow star in the vicinity of 1 $M_\odot$ is probably most conducive to the development of complex life forms on a temperate moist planet. The life of the star is long enough to provide the time necessary for biological evolution. The color temperature is such that the radiation penetrates through the planetary atmosphere and has enough energy per photon to provide effective photosynthesis. Conditions on a planet circling an M dwarf would be quite different and difficult to imagine without more specific facts. Similarly for an A star with its extremely intense UV and relatively short life.

The mass range for stars seems to be defined by the requirement that the object shines sufficiently brightly and for a sufficiently long time to be recognized in a stellar census. Thus, for instance, the conspicuous O and B stars provide a substantial portion of the radiation in a galaxy but are relatively rare for the simple reason that they convert their hydrogen into helium so quickly and have correspondingly short lives. In this respect one expects an upper limit of the order of $10^2\ M_\odot$ for stars on the Main Sequence.

It is apparent from observation that self-gravitating objects are formed all the way down to the mass of the terrestrial planets, and even to the satellites of the planets, with the numerous smaller objects arising on the periphery of the more massive objects. When we look to the protostellar cloud, we infer that it forms in a gaseous background that is subject to both Jeans' gravitational instability and a thermal instability. The protostellar cloud and subsequent accretion disk must be massive enough to be self-gravitating and cool enough to allow the escape of essentially all of the initial interstellar magnetic field, because it appears (Boyer and Levy, 1984; Boruta, 1996) that there is a magnetic field of no more than a few gauss in the interior of a star like the Sun. The angular momentum and magnetic field of the initial gravitating cell of interstellar gas determine the multiplicity of the final masses that condense into stars. Planetary bodies are expected only when there is a single star.

Objects like Jupiter are supported against gravity by the strength of the atomic electron structure in their cores. Somewhat more massive objects cannot be supported in that way so their central regions compress until they become electron degenerate. The Pauli exclusion principle guarantees support against gravity, and the support is stable so long as the highest occupied electron states are nonrelativistic. This is guaranteed because the temperature of the degenerate core is not high enough for nucleons to penetrate each other's Coulomb barriers to initiate thermonuclear reactions, and we have a brown star at most. The true stars, on the Main Sequence, are massive enough that the temperature reaches thermonuclear levels before they become internally degenerate. So it is electron degeneracy that sets a lower limit in the vicinity of $0.05\ M_\odot$ for the true star, leaving the old question of how many brown or dark objects there may be unseen in the Galaxy. How many MACHOS?

The virial theorem tells us that the more massive the object the higher the internal temperature at a given density. The quantum mechanical tunneling through nuclear Coulomb barriers is extremely slow and temperature sensitive at the low temperatures of stellar interiors. Thus, for instance, the mean thermal energy at the center of the Sun is 1.5 keV whereas the Coulomb barrier for $p - p$ reactions is of the order of 10^3 keV. The extreme rate of increase of nuclear reaction rates with increasing temperature means that a star with a mass of 10 $M_\odot$ has a central temperature only a little more than a factor of two higher than the Sun, whereas the luminosity and the overall thermonuclear reaction rate is 5×10^4 times larger. The thermonuclear rate per unit mass is, therefore, 5×10^3 times larger than in the Sun as a consequence of the somewhat higher temperature.

It is not without interest to write down some of the basic numbers. At the center of the Sun, where $T \sim 1.5 \times 10^7$ K, $\rho \sim 115$ g cm^{-3}, and the number density is 10^{26} protons cm^{-3}, a proton has a mean free path for nuclear collisions of about 1 cm. A mean thermal velocity of 10^8 cm s^{-1} provides a collision rate of about 10^8 s^{-1}. Over the 10^{10} yr thermonuclear life of the hydrogen in the core a proton makes of the order of 3×10^{25} nuclear collisions before penetrating a Coulomb barrier and participating in a nuclear reaction. In contrast, the star of 10 $M_\odot$ is 5×10^4 times brighter with a central temperature of 3.5×10^7 K (3.5 keV) and a central density of 10^{-1} the density at the center of the Sun. Hence a proton makes only 10^{21} hard collisions before participating in a nuclear reaction during the relatively short life of 2×10^6 yr of the star.

Note, then, that the brilliant photosphere of the Sun that we see with dazzled eyes might better be thought of as the outer surface of a dark and immensely opaque shroud, enclosing a central core that is preserved for 10^{10} yr and yet is substantially brighter than a supernova, which may be 25 magnitudes, i.e., a factor 10^{10}, brighter than the visible Sun. Consider a spherical surface of radius r centered in the Sun. The thermal radiation passing in both directions across the surface is $L(r) = 4\pi r^2 \sigma T(r)^4$, where σ is the Stefan–Boltzman constant (5.7×10^{-5} ergs cm^{-2} s^{-1} K^{-4}). It is readily shown from the standard solar model that $L(r)$ is a maximum at $r = 0.16\, R_\odot = 1.1 \times 10^{10}$ cm where $T = 1.0 \times 10^7$ K. The result is the radiative flux $L = 0.9 \times 10^{45}$ ergs s^{-1}, with the peak of the black body spectrum at 4.3 keV (X-rays at 3 Å). This is about 2×10^{11} times brighter than the Sun, of some 4×10^{33} ergs s^{-1} and substantially more than the peak luminosity of a supernova. Another way to put it is that the surrounding shroud reduces the radiative outflow by a factor of 2×10^{11}. The core of the Sun is wrapped up so warmly that it endures for 10^{10} yr with an overall solar metabolic rate of only 2 ergs g^{-1} s^{-1}. This is to be compared with the metabolic rate of the average human (100 W and 70 kg) of 1.4×10^4 ergs g^{-1} s^{-1}, which is almost 10^4 times larger, and three times the metabolic rate of the 10 $M_\odot$ star mentioned above. Put enough people together and you have an O star.

It is interesting to note the chance coincidence that the surface temperature (5600 K) of the Sun and the temperature at the center of Earth are about the same. So at the center of Earth the radiation field is as yellow and intense as the dazzling surface of the Sun.

The colossal central fireball in the Sun is stably confined by the gravitational field and by the immense overlying mass and opacity which controls the tiny leakage of heat to the visible surface. It is the immense opacity and the miserly leakage of heat that allows the Sun a life of 10^{10} yr on the Main Sequence. If the opacity were reduced in some way, the Sun would contract until the central temperature increased to where thermonuclear reactions would keep up with the greater energy loss from the surface, with a corresponding decrease in the life of the Sun.

Finally, note the point made by Eddington (1926) that the visible stars comprise those self-gravitating objects in which the central thermal gas pressure and radiation pressure are within a factor of 10^2 of each other. He showed that at 0.5 $M_\odot$ the central radiation pressure is only a little more than 1% of the gas pressure, whereas at 20 $M_\odot$ it is the other way around. Since the ratio of specific heats y for the radiation field has only the marginal value of $\frac{4}{3}$, it is clear that the massive star is less stable than the star of 1 $M_\odot$ or less, for which the effective γ in the core has the kinetic value of $\frac{5}{3}$.

The mass spectrum of small self-gravitating objects of nebular origin is known only from the sample of planets and satellites that we can see in the solar system. It is not obvious that a meaningful theoretical deduction of the mass spectrum of planets satellites, and sub-brown stars can be made for so complex a process. We have wondered how often a faint star drifting slowly through a dense molecular cloud may enhance a gravitational concentration of the cold gas. How many bright young stars have been built around an old brown star? It is not obvious that such an origin would provide any telltale signs in the newly formed bright star. There is the obvious, but probably small, possibility that the Sun is such a star.

3. Some History

It is useful at this point to summarize some of the major historical developments in macrophysics that came about through close study of Earth and the Sun and precise application of the mathematical laws of physics. For instance, we think we know the age of the Sun because we know the age of Earth from studies of the lead isotope ratios arising from thorium and uranium decay in crustal rocks. The assumption is that Earth and the Sun were formed at the same time in the same nebular condensation. Then we know something about the past luminosity of the Sun because the geological record shows that the terrestrial climate has always been temperate, with the continual deposition of water borne sediments. The surprising fact is that this temperate climate has been maintained in spite of the substantial theoretical evolutionary brightening of the Sun, on which we will have more to say later.

We know the mass of the Sun from the radius and period of the orbit of Earth and Cavendish's laboratory measurement of the gravitational constant G. We know the luminosity of the Sun from the intensity of sunlight at Earth. We know the relative abundances of the elements at the visible surface of the Sun from observations of the solar spectrum and the standard theoretical model atmosphere. However it should be remembered that the chemical composition of the Sun posed a baffling problem for many years. The solar spectrum is dominated by the lines of atoms with low first ionization potential, e.g., C, Ca, Na, Si, Fe, etc., as a consequence of the low surface temperature of 5600 K, which is simply not capable of exciting stiffer electron structures. Thus hydrogen and helium show only faintly. One of the many clues to the dominant abundance of hydrogen was the prohibitively large opacity of a gas made up primarily of the aforementioned metals. The continuum absorption in the photosphere was baffling until the existence of the negative hydrogen ion was realized. The development of quantum mechanics through the twenties and thirties made it possible (cf., Rosseland, 1936) to carry through the immense calculation of the properties of the negative hydrogen ion (Chandrasekhar, 1944; Chandrasekhar and Breen, 1946; Chandrasekhar and Münch, 1946; Chandrasekhar and Elbert, 1958). The structure of the photosphere was subsequently deduced from the measured wavelength dependence of the center-to-limb variation of the photospheric emission (Minnaert, 1953).

The first ideas of the internal structure of the Sun were obtained from the polytropic ($p \sim \rho^{\gamma}$) self-gravitating spheres computed by Lane (1869) and Emden (1907; see also Eddington, 1926; Chandrasekhar, 1939), adjusted to fit the total mass and radius. The opacity was not known beyond the equivalent of the classical Thomson scattering (recall the dilemma of classical physics with the orbiting electron and the absence of electromagnetic radiation) until quantum mechanics entered the field, making it possible to compute the opacity directly from the electron structure of the individual atoms. It is interesting, however, to see how far Eddington (1926) was able to infer the opacity prior to that time.

The energy source of the Sun was a baffling problem. Simple oxidation combustion is entirely inadequate. For instance, a Sun composed of carbon and oxygen would suffice for only a couple of thousand years. Hydrogen and oxygen would be but little better, and hydrogen was not appreciated as a major constituent. A more potent source of heat was pointed out by Helmholtz in 1854, and later by Kelvin, in the form of gravitational contraction. The rate of contraction would amount to no more than 40 m yr^{-1}, providing sunshine of increasing intensity for a period of several million years. Kelvin was so sure of this idea that he disavowed Darwin's concept of biological evolution because a few million years is nowhere near enough time for evolution to unfold to its present complexity. It was the geologists that blew the whistle on the Kelvin gravitational contraction theory, based on their studies of the formation and evolution of the crustal rocks, which required at least several hundred million years. With Einstein's statement of the equivalence of mass and energy it was realized that the immense energies involved in maintaining the Sun (4×10^{33} ergs s^{-1} or 10^{49} ergs for each 10^8 yr) required one to think in terms of the conversion of substantial quantities of mass into energy (4×10^{12} g s^{-1} or 10^{28} g for each 10^8 yr). This is about four times the mass carried away bodily by the solar wind. That is to say, sunshine represents a much larger mass loss to the Sun than the solar wind. It should be no surprise, then, that the radiation pressure of sunlight is about 2×10^3 times larger than the ram pressure of the solar wind.

Finally, note that the total mass loss over the estimated life of 10^{10} yr is only 10^{30} g, or $0.5 \times 10^{-3}\ M_{\odot}$.

Eddington (1926) thought in terms of subatomic particle conversion into energy. The advent of nuclear physics in the thirties provided the specific process, with Bethe identifying the carbon cycle and the $p - p$ chain, converting hydrogen to helium with about 1% of the mass released to energy (Bethe and Critchfield, 1938; Bethe, 1939; Weizsacher, 1938). Thus about 4×10^{14} g of hydrogen is converted to helium each second in the central core of the Sun. That amounts to converting about 3% of the hydrogen into helium in the 4.6×10^{9} yr the Sun has been on the Main Sequence, with another 3% to be converted by the time the central core is depleted of hydrogen and the red giant phase is reached.

These principles are so familiar that we tend to forget that each was a conceptual revelation in its time. Who in 1880 could have anticipated the advances in physics over the next 50 yr, and who could have anticipated the remarkable macrophysical principles and concepts to arise from those advances and from observation and contemplation of the Sun? The elegant mathematical and physical precepts of radiative transfer (cf., Chandrasekhar, 1950) and of the stellar interior (cf., Eddington, 1926; Chandrasekhar, 1939; Schwarzschild, 1960) are the final results of the many successive stages of the development. Pauli's statement of the exclusion principle for particles with spin $\frac{1}{2}$ led almost immediately to the theory of electron degeneracy in the interiors of white dwarfs (Fowler, 1926) and from there to the mass limit for white dwarfs (Chandrasekhar, 1931, 1935, 1969). The electron degeneracy was an offshoot based on the simple fact of the mass and extraordinary radius of the white dwarf.

The thermonuclear production and accumulation of helium in the core has the obvious effect of diluting the hydrogen and diminishing the nuclear burning rate so that the Sun compensates by contracting, increasing both the density and temperature so that the burning keeps up with the radiative loss from the photosphere. The increasing temperature means that the luminosity of the Sun increases with time. Quantitative theoretical models of the Sun, assuming no mixing of the stably stratified core, indicate that the Sun was originally about 30% fainter than it is today. As already noted, that inference raises a serious question because the geological record shows that the climate of Earth has always been temperate, with continuing deposition of clay, sand, and gravel in water to form sedimentary rocks. However, present-day global climate models suggest that a reduction of the present brightness of the Sun by 3–5% would lead to a gradual cooling and eventual freezing all the way to the equator as the oceans cool over a period of 500 or 1000 yr. Earth would become a snowball. The models go on to suggest that turning the Sun back up to its present brightness would not thaw the frozen Earth and return it to its present temperate state because of the high albedo of the snow covered planet. Now one may presume that the early Earth had an atmosphere with more greenhouse gases, sufficient to compensate for the fainter sunlight. However it is necessary then to assume that the greenhouse effect declined at precisely the right rate to maintain a temperate climate while the Sun brightened by 30%. At no time did the oceans boil off or freeze over. Was it a stroke of luck that atmospheric evolution kept pace with the evolutionary brightening of the Sun? If so, it represents another factor in the probability that a terrestrial type planet develops complex life forms. Or are we misinterpreting the evolution of the thermonuclear core of the Sun? For instance, is there some mixing or diffusion process that limits the accumulation of helium in the core, thereby reducing the evolutionary brightening?

While we are on the subject of the central core of the Sun, consider the implications of the very low limit of 30 G inferred by Boyer and Levy (1984) and Boruta (1996) from the absence of any strong north-south asymmetry of the dipole magnetic field component of the Sun. The essential point is that the collapse of an interstellar gas cloud to form a star is expected to sweep in the interstellar magnetic field entrained in the gas. Initial fields of 10^6 G or more might be expected in the high density core of the Sun. Cowling (1953) noted fifty years ago that the characteristic resistive diffusion and decay time of a dipole magnetic field in the central core of the Sun is about 10^{10} yr, indicating that any initial dipole field component would still be with us, only slightly diminished but fully extended into the overlying envelope. Any such field would introduce a strong fixed bias in the alternating dipole field of the Sun. Boruta puts a conservative upper limit of 30 G in the absence of any significant observed fixed bias, so we are left with the clear idea that the formation of the Sun swept in little or none of the interstellar magnetic field that initially threaded the gas before condensing to form the Sun. This implies a very cold proto solar nebula as well as a nebula so dense as to keep out the ionizing cosmic rays, requiring a thickness in excess of 1 kg cm^{-2}. It also raises questions whether there was any significant magnetic field in the proto solar accretion disk.

Turning again to the observations of solar neutrinos, the standard model of the Sun seems to be in conformity with helioseismology while the laboratory neutrino detection rates for the several different energy ranges of the various thermonuclear reactions in the Sun are about half or a third the expected values computed from that model. Only electron neutrinos are emitted by those thermonuclear reactions. Four independent electron neutrino detectors have been in operation for several years now, with the Homestake chlorine detector for 25 yr, sensitive to neutrinos above 0.8 MeV. The two gallium detectors have a much lower threshold of 0.2 MeV while the Kamiokande Čerenkov detector picks up only those at 7 MeV or more, for which it yields the direction of arrival. Thus Kamiokande senses the neutrinos only from ^{8}B, while Homestake looks mostly at ^{7}Be, and the Gallium detectors, with a threshold of 0.2 MeV, catch all of the reactions including the basic $p - p$ reaction. The essential point is that each detector records about a half or a third of the expected neutrino flux. This suggests that the neutrinos from the Sun may be subject to oscillations from their electron neutrino form to μ and τ neutrinos, which would not be seen by the aforementioned electron neutrino detectors. Oscillations would occur only if the electron neutrino has a rest mass, which would be very interesting indeed. In any case the present situation suggests that there is some fundamental neutrino physics to be learned. Accordingly a number of new neutrino detectors are in the works, with the Super Kamiokande detector coming into operation in 1996. The Sudbury Neutrino Observatory (SNO) comes on line in 1997. The essential feature of the new experiments is their detection of each individual neutrino event, measuring the energy of the incoming neutrino as well as its direction of arrival. Equally important, the detection rates are high enough that useful statistics are accumulated each year. Super Kamiokande does not distinguish neutrino types and will detect mainly electron neutrinos, while the SNO uses heavy water and will distinguish between different types of neutrinos by measuring the breakup of the deuterium nuclei in the heavy water. The BOREXINO detector in the Gran Sasso laboratory is expected to begin operations in 1999 with a threshold at 0.2 MeV, and at least two different neutrino detectors are in the planning phase at the same laboratory. The intensity of the effort indicates the seriousness of the physics involved here. Hopefully it will not be many years before this intensive investigation will begin to clear up the problem. The work is doubly interesting because it may have both thermonuclear and cosmological implications beyond the basic neutrino physics. That all remains to be seen, of course, because we have no idea what new twists and turns may arise in the course of the investigation (cf., Bahcall and Halzen, 1996).

Now it must be appreciated that the historical development of a model of the interior of the Sun depends upon the development of the macrophysics of the atmosphere of the Sun, for it is only in the atmosphere that one can hope to determine the elemental abundances, as already remarked. So it is not surprising that the pursuit of the physics of the atmosphere and interior ran parallel for many years. The determination of the vertical structure of the photosphere was a monumental achievement, using the center-to-limb darkening as a function of wavelength, as already noted. This construction is something that can be accomplished for no star other than the Sun, and the vertical structure is essential for inferring the elemental abundances from the observed spectrum. Minnaert (1953) gives an historical account of this undertaking. Once the physics of the solar photosphere is understood, it is possible to turn to other stars, of course. It becomes a nontrivial exercise in quantum statistical mechanics, in which one may have confidence because of the success with the center-to-limb information available from the Sun.

Turning to the solar interior (cf., Strömgren, 1953) the next step is to compute the opacity of the gas (cf., Rosseland, 1936) as a function of density and temperature based on the assumption that the elemental abundances at the surface reflect the abundances deep inside. Any such assumption is critical because of the disproportionately large contribution of the heavy elements to the total opacity. There are obvious corrections to the surface abundances in the thermonuclear core, with the conversion of hydrogen into helium. There are also some more subtle effects that may have important effects as well, such as the gravitational settling of the heavier elements, wave driven diffusion (Schatzman, 1993, 1996; Morel and Schatzman, 1996) and the tendency for the more highly charged ions to diffuse toward higher temperature (Chapman, 1958). Fortunately helioseismology is able to serve as an independent check on the gross features of theoretical models of the interior of the Sun. The successful theoretical construction of the solar photosphere and interior is a monumental achievement, carried out by the efforts of many scientists over the past century.

4. The Suprathermal Atmosphere

The next great leap in stellar macrophysics was the recognition of the chromosphere and corona as suprathermal phenomena, i.e., kinetic temperatures far above anything that can be explained by the great outpouring of thermal radiation from the 5600 K photosphere. Extrapolation of isoelectronic series from laboratory measurements of the spectra of neutral, singly ionized, doubly ionized, etc. atoms (Grotrian, 1931, 1933, 1939) led to the identification of coronal emission lines (Lyot, 1939) as ten or more times ionized Si, Fe, etc. (Edlen, 1942; Waldmeier, 1945). It became clear that the corona is an extended atmosphere with a temperature of some 10^6 K or more, and a pressure scale height in excess of 5×10^4 km. Measurements of the thermal radio emission soon confirmed the high temperature, and the work of Billings (1959) placed the various temperature determinations in proper perspective. The thermal X-ray emission from the corona was first detected by Burnight (1949) with photographic emulsion wrapped in metal foil and lofted above the atmosphere with a German V-2 rocket (Friedman, Lichtman, and Byram, 1951). The field of X-ray astronomy originated with this pioneering work at the Naval Research Laboratory. The first X-ray photographs of the Sun were achieved in 1960 with a pinhole camera, showing a clear correlation with the plage areas (magnetic regions) on the Sun (Friedmann 1961). The development of the grazing incidence X-ray telescope led to enormously improved resolution (cf., Tousey *et al.*, 1973; Vaiana *et al.*, 1973; Underwood *et al.*, 1976, Reeves *et al.*, 1976), with the normal incidence X-ray telescope now providing resolution down to 1 arc sec or better (Walker *et al.*, 1988; Golub *et al.*, 1990; Golub, 1991). As is now well known, the X-rays represent thermal emission, i.e., bremsstrahlung, from filaments of hydrogen plasma of 10^{10} atoms cm^{-3} and $1–8 \times 10^6$ K lying along the 10^2 G bipolar magnetic fields of active regions. The surface brightness of the X-ray emission may be as high as 10^7 ergs cm^{-2} s^{-1} and depends little, if at all, on the length of the bipole, which may be as small as 10^4 km and as large as 2×10^5 km (Rosner, Tucker, and Vaiana, 1978).

The chromosphere has been known for centuries as the ‘red flames’ that appear around the limb of the Moon during a total eclipse of the Sun. The chromosphere is a patchwork lying between the photophere and the corona, and can be studied with rapid spectroscopy as the dark limb of the Moon progressively covers or uncovers the limb of the Sun. The temperature of the chromosphere was determined to be in the range 6000–9000 K indicating a nonthermal energy source (Biermann, 1948; van de Hulst, 1953), e.g., the dissipation of sound waves and internal gravity waves (Whitaker, 1963) generated by the subsurface convection. The theoretical interpretation of the chromospheric spectrum was at the center of the LTE versus non-LTE debate and was crucial in establishing the importance of non-LTE in stellar atmospheres, as noted earlier.

The flare phenomenon is the most suprathermal of all, occasionally accelerating protons to relativistic energies so that the concept of temperature has no useful application to the overall process. The close association of flares with strong active magnetic fields was conspicuous (cf., Kiepenheuer, 1953), and it was known at the turn of the century that strong geomagnetic disturbances tend to follow a day or two after a large flare on the Sun. Kelvin showed, then, that if space were a hard vacuum, the geomagnetic disturbances could not be a direct consequence of magnetic variations at the Sun. From this he made the curious declaration that there could be no connection to solar activity in spite of the clear correlation, while others, e.g., Fitzgerald, pointed out the idea of corpuscular emission from the Sun. Chapman developed the idea of solar corpuscular radiation from flares as the cause of terrestrial magnetic storms (Chapman and Ferraro, 1931, 1932, 1933, 1940). So a new macrophysical concept emerged, to the effect that a star like the Sun emits fast ($\sim 10^3$ km s^{-1}) particles, presumably electrons and protons. Forbush (1946) established the production of relativistic particles at the time of flares, or ‘solar cosmic rays’. Giovanelli (1947, 1948) speculated that a flare was an electrical discharge in a varying magnetic field and Dungey (1953) noted the special properties of an X-type neutral point in a magnetic field. The great flare of 23 February 1956 demonstrated the extraordinary efficiency for producing relativistic protons (cf., Meyer, Parker, and Simpson, 1956), and the enormous total energy of that flare provided clear evidence that the only sufficient energy source for the flare is the magnetic field (Babcock, 1947, 1958; Babcock and Babcock, 1955) in which the flare occurs (Parker, 1957a; Sweet, 1969). Sweet (1958a, b) pointed out the rapid dissipation of magnetic energy where two opposite fields press against each other, and the merging rate of two such fields was estimated (Parker, 1957b) to be the characteristic Alfvén speed divided by the square root of the Lundquist number. Unfortunately the estimated rate was too small to provide the energy indicated by the explosive flare phenomenon, and it was not until Petschek (1964) and Petschek and Thorne (1967) demonstrated a faster mode of dissipation and field reconnection that the theoretical basis for the flare began to take shape. The concept of rapid reconnection is then another important macrophysical principle, whose discovery was motivated by the extraordinary suprathermal energy displayed by the solar flare.

Now it was clear by 1960 that the activity of the Sun is basically magnetic in origin. If for some reason there were no magnetic fields, there would be little more suprathermal activity than the chromosphere. So it is interesting to note that new and unexpected magnetic phenomena began to be discovered at an accelerated rate, with the realization of the astonishing fibril state of the photospheric magnetic field around 1970 (Leighton, 1963; Beckers and Schröter, 1968; Livingston and Harvey, 1969; Simon and Noyes, 1971; Howard and Stenflo, 1972; Frazier and Stenflo, 1972; Chapman, 1973). The mysterious spontaneous clustering of magnetic fibrils to build up magnetic pores and sunspots was realized by 1980 (Zwaan, 1978, 1985; Gaizauskas *et al.*, 1983). The spectacular coronal mass ejection was discovered by the *Skylab* observations (see review by Low, 1996).

By 1976 Eddy (1976, 1977a, b) had established that the Sun has switched off its magnetic activity for ten out of the last 70 centuries and has operated in a state of hyperactivity in eight other centuries, greatly extending the earlier work of Maunder (1894) and Clerke (1894) on the Maunder Minimum of 1645–1715. Eddy (1977a, b, 1980, 1983) and Ribes and Nesme-Ribes (1993) also pointed out the curious climate in the northern temperate zone in these extraordinary centuries, with the mean annual temperatures depressed 1–2 °C when the Sun was inactive and elevated by a similar amount when the Sun was hyperactive. The startling discovery of the systematic variation in the brightness of the Sun (by about 0.2%) with the 11-yr variation of solar activity was firmly established by 1994 (Willson and Hudson, 1988; Hoyt *et al.*, 1992; Friis-Christensen and Lassen, 1991; Zhang *et al.*, 1994) providing the explanation for the climatic variations pointed out by Eddy (see also Beer *et al.*, 1994).

One may presume that the magnetic fields (Hale, 1908a, b; Babcock and Babcock, 1955) responsible for the activity are generated in some form of $\alpha\omega$-dynamo process somewhere deep in the convective zone (Parker, 1955b, 1957c, 1979, 1993; Moffatt, 1978; Krause and Rädler, 1980; Speigel and Weiss, 1980), but there is still no precise idea on the form of the dynamo and still no clear physical picture of the 'turbulent diffusion', or equivalent dissipation, of some 10^{11}–10^{12} cm^2 s^{-1} that is an essential part of the dynamo. Dimensional analysis and mixing length concepts applied to the convective zone suggest that there may be such diffusion and dissipation, but dimensional analysis hardly rates as a proper theoretical understanding. It appears that the fibril state of the magnetic field may play a role, but so little is known about the dynamical behavior of the fibril field in the Sun (Parker, 1978, 1979b, 1982, 1995) that its role in the dynamo process can only be speculated upon (cf., Vainshtein, Parker, and Rosner, 1993; Parker, 1996b). Here we see that the two distinct concepts of the magnetohydrodynamic $\alpha\omega$-dynamo and the fibril magnetic field structure may be interrelated, in some way that we do not yet understand. Some new macrophysical principle is yet to be discovered.

Stepping back from these fascinating and puzzling phenomena, it is clear that macrophysics, through turbulent convection in a rotating body, encompasses many physical effects of which we are unaware. The story evidently begins with the inability of radiative transport to handle the outward heat flow in the outer 2×10^5 km of the solar radius. That sets the great convective heat engine in motion (cf., Schwarzschild, 1958), and the curious magnetic activity is somehow the result. The first problem is the convection itself, insofar as it can be understood without including the stresses of the magnetic fields that it generates. The peculiar internal rotational state of the Sun, with the angular velocity depending largely on latitude in the convective zone and nearly uniform throughout the radiative interior, is strikingly different from the simple dependence on distance from the spin axis arising in most theoretical models. The strong vertical stratification evidently plays an important role in shaping the distribution of angular velocity, and is exceedingly difficult to treat either analytically or numerically (cf., Durney, 1993). So we are not yet in a position to deduce the precise form of the convection, and certainly not in a position to deduce the precise form of the solar dynamo, or anything much at all about the consequent activity. However, observations have already led to an *ad hoc* theoretical understanding of several separate pieces of the physics of the larger overall puzzle. For instance, as already noted, the facts of the solar flare phenomenon have led to the concept of rapid reconnection of magnetic fields. The emerging bipolar magnetic fields imply an underlying azimuthal magnetic field in the deep convective zone (Cowling, 1953) and their arrival at the surface is to be understood in terms of magnetic buoyancy (Parker, 1955a, 1966, 1979a), The recognition of hydrodynamic expansion of the million degree corona, providing the solar wind and heliosphere, is a direct outgrowth (Parker 1958a, 1963, 1969) of the observations, even if we still do not know precisely how the coronal holes are heated. On the other hand, the observational studies of the X-ray corona define the problem of its heat source to such a degree that the general theory can now be suggested (Parker, 1994). And there remains a variety of phenomena about which we understand little or nothing, as mentioned earlier.

Now the historical triumphs of the macrophysics of the Sun right up to the present day are all simple in their general principles and one might say obvious in retrospect. However, they were neither obvious nor simple before the fact, and indeed involved unfamiliar concepts at the times they were achieved. Their discovery was possible only by paying strict attention to the observations and strict quantitative attention to the physics indicated by the basic mathematical laws. In the theoretical studies that established the principle, ideas were not rejected because they were out of line with the established 'wisdom' but only if truly excluded by observations or by the mathematical laws. For it must be remembered that new macrophysics by definition lies outside the conventional 'wisdom', and for that reason is often slow to be accepted in the general scientific community.

In the years ahead we will direct attention to the many macrophysical phenomena on the Sun for which the observations have not yet succeeded in defining the precise problem, as noted in the Introduction. Often the problem seems to grow more puzzling as the observations progress. For instance the fibril magnetic field of $1{-}2 \times 10^3$ G at the photosphere is now supplemented by the theoretical inference that there are fibrils of 5×10^5 G or more at the bottom of the convective zone (D'Silva,1993; D'Silva and Choudhuri, 1993; Fan, Fisher, and De Luca, 1993). Such intense fields overpower everything but the barometric forces in the superadiabatic convection zone and appear to be associated with the continual emergence of Ω-loops of azimuthal field (Parker, 1984, 1994b) thereby relating them to the varying brightness of the Sun (Parker, 1994c, 1996b). However, this remains speculative until observations can define the subsurface motions more directly. The origin of the small-scale bipolar magnetic fields that continually emerge in the supergranules more or less independently of the 11-yr magnetic cycle (Martin and Harvey, 1979; Golub, Davis, and Krieger, 1979; Golub and Vaiana, 1980) is another puzzle reminding us that there is much that is missed by our simple dynamo models for the Sun. Not only do we fail to understand the high rate of diffusion and dissipation of the large-scale magnetic fields in the Sun, but there is evidently much of which we are simply unaware. With the intensive observational studies presently underway we may hope to see how these things fit together someday.

To illustrate the elementary nature of the macrophysical principles of some aspects of solar activity, and to show the necessity for working from first principles, we review briefly the observational and theoretical basis for the solar wind and for the X-ray corona.

5. The Corona, the Solar Wind, and the Heliosphere

The expansion of the gravitationally bound solar corona to produced the supersonic solar wind illustrates the importance of (a) using the observations to constrain the theoretical possibilities, and (b) accepting the inescapable but counter-intuitive results of a direct integration of Newton's equation of motion. The initial psychological barrier to accepting the result stemmed from the conviction that the corona is strongly bound by gravity and therefore can only evaporate some of the faster ions and electrons into space. For the mean thermal energy of the coronal gas is only about a tenth of the gravitational binding energy. On the other hand, observations and their elementary theoretical interpretation demanded something else. This is all four decades old now and the lesson largely forgotten, insofar as it was noticed at the time. So we give a brief summary of the facts from the time when space was viewed as a vacuum apart from an occasional beam of corpuscular radiation from the Sun.

The development of the concept got underway when Biermann (1948, 1951, 1952, 1957) noted the prevailing solar corpuscular radiation, always blowing gaseous comet tails away from the Sun, irrespective of the direction of motion of the comet, irrespective of the heliocentric latitude of the comet, and irrespective of the presence of magnetic active regions on the Sun. During the same period Simpson (1954) and Meyer and Simpson (1954, 1957) showed that the energy dependence of the variations in the intensity of the galactic cosmic rays indicated manipulation by time varying magnetic fields in interplanetary space, as distinct from the electrostastic fields commonly postulated for an entirely empty space. The rise and decay of the relativistic protons from the flare of 23 February 1956 showed clear passage from the Sun to Earth with some form of magnetic barrier not far beyond Earth (Meyer, Parker, and Simpson, 1956).

At about the same time Chapman (1954, 1959) noted the extraordinarily large thermal conductivity provided by the electrons in the solar corona. He also noted the negligible radiative cooling of the tenuous coronal gases, and from these facts he showed that the temperature of the corona declines only very slowly with radial distance r, essentially as $r^{-2/7}$ (Chapman, 1954, 1958). The barometric condition for static equilibrium is

$$\mathrm{d}\ln p/\mathrm{d}r = 1/\Lambda(r) \ , \tag{1}$$

for ionized hydrogen for which $\Lambda(r)$ is the scale height $2r^2kT(r)/GM_{\odot}M$ and M is the mass of a hydrogen atom. Chapman then showed that the solar corona extends out well beyond the orbit of Earth.

Note that the origin of solar corpuscular radiation was not at all clear in those days. Most of us thought vaguely in terms of some electromagnetic process, perhaps associated with flares or sunspot magnetic fields in view of the correlation of geomagnetic disturbances with flares on the Sun. Biermann's evidence of universal solar corpuscular emission was baffling.

By 1957 the two-stream plasma instability was known, from which it followed that one tenuous (collisionless) plasma cannot pass freely through another tenuous plasma: perturbations of the electron density in one excite perturbations in the electron density in the other, and the perturbations provide an electrostatic interaction between the two that increases the density perturbations on time scales of the order of the ion plasma period. It was obvious from this that the ideas of Biermann and Chapman were mutually exclusive. Biermann's solar corpuscular radiation could not pass freely through Chapman's extended corona. On the other hand, the ideas of Biermann and Chapman were hard to escape.

It must be appreciated that in those days the large-scale dynamics of a collisionless plasma was not clearly understood. The gradient and curvature drifts of the individual ions and electrons produced currents whose effects were not immediately obvious, although in retrospect there need not have been any confusion. Newton's law of motion was applicable and was known to be entirely compatible with Maxwell's equations in the nonrelativistic limit. Thus the large-scale bulk motion must be described by the familiar hydrodynamic equation, with perhaps an anisotropic pressure tensor, because that equation is nothing more than the statement of the time rate of change of the mean momentum in any fixed volume. It is curious that some authors are still confused on this point today (Parker, 1996a, c).

Note from Poynting's theorem that the electromagnetic field represents a stress field described by the Maxwell stress tensor

$$M_{ij} = -\delta_{ij}(E^2 + B^2)/8\pi + (E_iE_j + B_iB_j)/4\pi \ .$$

The bulk motion u_i of a plasma represents a momentum flux given by the Reynolds stress tensor

$$R_{ij} = \rho u_i u_j \ , \tag{2}$$

where ρ is the local mean density of the plasma. The thermal motions relative to u_i may be denoted by w_i and their momentum flux has an average value

$$p_{ij} = \Sigma m w_i w_j \ , \tag{3}$$

where m is the particle mass and the sum is over unit volume. It follows from Newton's law of motion that the momentum density ρu_i of the bulk motion satisfies the conservation equation

$$\partial \rho u_i/\partial t + \partial p_{ij}/\partial x_j = \partial R_{ij}/\partial x_j + \partial M_{ij}/\partial x_j \tag{4}$$

irrespective of particle collisions.

The problem is to compute p_{ij}, of course. The most direct approach is a complete particle simulation, taking advantage of the fact that we are interested in the large-scale bulk motion of a plasma. That is to say the scale l of variation of the electromagnetic fields and of the bulk velocity u_i is large compared to the cyclotron radius of the individual particles. The guiding center approximation is then appropriate for describing the motion of the individual particle. In that case let $\mathbf{u} \equiv c\mathbf{E}\times\mathbf{B}/B^2$ represent the electric drift velocity of the ions and electrons noting that in that frame of reference there is no electric field on scales larger than the Debye radius. In the fixed frame the total electric field is $\mathbf{E} = \mathbf{E}_{||} - \mathbf{u}\times\mathbf{B}/c$, where $\mathbf{E}_{||}$ is the electric field component parallel to $\mathbf{B}$. For large-scale, slowly evolving bulk motion, plasma isntabilities feed on any thermal anisotropy, so that before long the thermal motions approximate closely to isotropy. Interesting exceptions can be constructed in special cases of very tenuous plasma in strong magnetic fields, for which the plasma instabilities are weak and slowly growing. However, for the quasi-static solar corona isotropy appears to be an excellent approximation. We suppose that the plasma density is sufficiently high that electron conduction velocities associated with the weak electric current density in the large-scale magnetic field are small. As we shall see, the electric current is automatically taken care of by the gradient, curvature, and polarization drifts of the guiding center approximation. Thus we expect to find no significant $\mathbf{E}_{||}$. Therefore, except in regions of rapid field variation, e.g., an auroral current sheet, the magnetopause, the current sheet in a flare, etc., we have the familiar relation $\mathbf{E} = -\mathbf{u}\times\mathbf{B}/c$, so that the Maxwell stress tensor reduces to

$$M_{ij} = -\delta_{ij}B^2/8\pi + B_i B_j/4\pi \tag{5}$$

if we neglect terms second order in u/c compared to one. It is then a straight forward but tedious geometrical exercise to sum over the gradient, curvature, and polarization drifts of the particles in an electrically neutral plasma to obtain an expression for the current density $\mathbf{j}$. Substituting the result into Ampère's law (since $\partial\mathbf{E}/\partial t$ is small to second order) the result is

$$\rho \, \mathrm{d}\mathbf{u}/\mathrm{d}t = -\nabla_\perp(p_\perp + B^2/8\pi) + [1 - 4\pi(p_{||} - p_\perp)/B^2]\,[(\mathbf{B}\cdot\nabla)\mathbf{B}]_\perp/4\pi \tag{6}$$

for the motion perpendicular to $\mathbf{B}$, where $p_\perp$ is the pressure perpendicular to the magnetic field, equal to $\Sigma m w_\perp^2/2$, and $p_{||}$ is the pressure parallel to the magnetic field, $\Sigma m w_{||}^2$. This is, of course, nothing more than the usual magnetohydrodynamic momentum equation in the presence of a thermal anisotropy, $p_{||} - p_\perp \neq 0$, in the plasma. The extra term represents the centrifugal force of the thermal motions along the curved field lines (Parker, 1957a). In the quasi-static corona the centrifugal term may be dropped and the bulk motion parallel to B approximates to

$$\rho \, \mathrm{d}\mathbf{u}_{||}/\mathrm{d}t = -\nabla_{||} p \; . \tag{7}$$

The large-scale bulk motion of a collisionless plasma is nothing more than hydrodynamics in the presence of the Lorentz force $\partial M_{ij}/\partial x_j$. Indeed the result could be nothing else because Equation (4) is the general statement of conservation of momentum in any local fixed volume through which the particles are streaming. As noted earlier, the equations of Newton and Maxwell are mutually consistent, for if they were not, one or the other of them would be violated.

Note that with $\mathbf{E} = -\mathbf{u} \times \mathbf{B}/c$ the induction equation becomes

$$\partial \mathbf{B}/\partial t = \nabla \times (\mathbf{u} \times \mathbf{B}) \; . \tag{8}$$

The magnetic field moves precisely with the electric drift velocity of the plasma. That is to say, the magnetic field moves in the frame of reference in which there is no electric field, and that frame of reference is determined by the bulk motion of the plasma according to Newton's equation.

The basic equations (4)–(8) tell us that the bulk motion of a plasma is determined by the dynamical interaction between the magnetic stresses and the pressure and momentum of the plasma. The electric currents required by Ampère's law are automatically provide by the detailed motion, i.e., the curvature and gradient drifts, of the individual ions and electrons. The currents represent no significant stress or energy in the large-scale plasma and field. They are driven by $\mathbf{E}$ and $\mathbf{B}$, and if collisions between ions and electrons were to provide a resistivity, the energy needed to maintain the currents required by Ampère would come from $\mathbf{B}$. Noting that

$$\partial \mathbf{E}/\partial t = c\nabla \times \mathbf{B} - 4\pi \mathbf{j} \; ,$$

it is evident that whenever $\mathbf{j}$ falls short of Ampère's law, there is a rapid growth of $\mathbf{E}$ that quickly forces the ions and electrons to supply the required $\mathbf{j}$. The electric currents are driven by the magnetic field. In fact, as already noted, the currents are a natural and direct consequence of the individual electron and ion motions in the moving magnetic field and plasma.

What then are we to make of the Biermann–Chapman conflict? Each made a point that could not be avoided. It became clear that the only reconciliation was that they were both correct and each was talking about different aspects of the same thing. Chapman's extended static corona was strongly bound by the gravitational field of the Sun, while Biermann's corpuscular radiation at large distance from the Sun must be part of that same corona, in some way accelerated at large distance (where it is not gravitationally bound, the thermal velocity greatly exceeding the gravitational escape velocity at large radial distance r) to velocities of 500 km s^{-1} or more. Biermann's and Chapman's inferences allowed no other possibility.

It was easy to show that with Chapman's static temperature profile $T(r) \sim r^{-2/7}$, the barometric equation (1) yields a coronal gas pressure that falls asymptotically to a nonvanishing value at infinity. A static corona can be achieved, then, only if there is a sufficient inward pressure from infinity. The typical interstellar pressure of 10^{-12} dynes cm^{-2} would not be adequate. So instead of the barometric equation (1), one should use the radial momentum equation for a stationary, rather than a static, corona,

$$NMu\,\mathrm{d}u/\,\mathrm{d}r = -\,\mathrm{d}NkT/\,\mathrm{d}r - GM_{\odot}NM/r^2\ , \tag{9}$$

for ionized hydrogen, for which $p = 2NkT$, and M again denotes the mass of the hydrogen atom with number density N. Ignoring the inertial term on the left-hand side gives precisely the barometric equation (1). Conservation of mass in a radial outflow velocity u requires that the product Nur^2 be independent of radial distance r, which can be used to eliminate N from momentum equation (9). The result can be written

$$(u - U^2/u)\,\mathrm{d}u/\mathrm{d}r = 2U^2/r - \mathrm{d}U^2/\mathrm{d}r - GM_{\odot}/r^2\ , \tag{10}$$

where $U^2 \equiv 2kT/M$ is a measure of the mean-square ion thermal velocity.

This momentum equation is easily integrated for a polytropic variation $p \sim N^{\alpha}$, but the simple isothermal case $\alpha = 1$ is sufficient to illustrate the principles. We seek a solution for a strongly bound quasi-static corona at the Sun for which the pressure falls to zero at infinity. That is to say $U^2 \ll GM_{\odot}/r$ at the Sun with N falling to zero at infinity, i.e., ur^2 increases without bound as r increases. There is only one such solution, and that is the solution passing straight across the sonic point where $u = U$ at $r = b$, where $b \equiv GM_{\odot}/2U^2$ is large compared to the radius of the Sun for a strongly bound corona. Both sides of Equation (10) vanish together as u crosses the sonic point. The solution can be written

$$u^2/U^2 - \ln u^2/U^2 = 1 + 4\ln r/b + 2(GM_{\odot}/U^2)\,(r^{-1} - b^{-1})\ . \tag{11}$$

For $r \ll b$ the velocity is small, with

$$u^2/U^2 \sim (b/r)^4 \exp[-1 + 2(GM_\odot/U^2)\,(b^{-1} - r^{-1})]\,, \tag{12}$$

if the gas is strongly bound by gravity. This is Chapman's quasi-static corona for uniform temperature, with the density varying in proportion to $\exp(GM_\odot/U^2 r)$ in spite of the small outward motion u. For $r \gg b$ the velocity is large compared to U, with

$$u^2/U^2 \sim F(r) + \ln F(r) + \ln F(r)/F(r) + \cdots\,, \tag{13}$$

where

$$F(r) = 1 + 4\ln r/b + 2(GM_\odot/U^2)\,(r^{-1} - b^{-1})\,. \tag{14}$$

The velocity increases asymptotically as $2U(\ln r/b)^{1/2}$. This is Biermann's solar corpuscular radiation (Parker, 1958a) and we called it the *solar wind*.

For the general polytropic case, $p \sim N^\alpha$, the velocity at infinity is supersonic and asymptotically constant for $\alpha < -\frac{3}{2}$. The pressure automatically falls to zero at infinity because the velocity approaches a constant, yielding $N \sim 1/r^2$ and $T \sim 1/r^{2(\alpha-1)}$. Thus for any $\alpha < \frac{3}{2}$ the temperature declines asymptotically less rapidly than r^{-1} so that the thermal energy exceeds the gravitational binding energy at sufficiently large distance, and the gas expands to infinity with finite, and therefore supersonic, velocity as the temperature falls to zero. Thus, no strongly bound atmosphere with an extended temperature in an otherwise empty space has a static state. The atmosphere can only expand, reaching supersonic velocity at infinity. Subsequent studies (Parker, 1965a, b) showed how cutting off the heat transport suppresses the distant temperature and reduces the supersonic wind to subsonic velocity at large r.

The supersonic expansion of an extended temperature is a simple principle of macrophysics, following from elementary considerations on Newton's equation. We came across the principle through Biermann's considerations on the comet activity in interplanetary space. Otherwise it would never have occurred to us.

There are a number of corollaries that follow upon application of the principle to the corona of the Sun (Parker, 1958a, 1963). For instance, any weak magnetic fields in the wind are transported radially through interplanetary space, forming an Archimedean spiral as a consequence of the rotation of the Sun. The outward sweep of the spiral magnetic field, which undoubtedly has many small-scale irregularities, reduces the intensity of the galactic cosmic rays by varying degrees in the inner solar system, thereby accomplishing the observed cosmic-ray variations (Parker, 1958b). The field is nearly radial inside the orbit of Earth, permitting the free passage of fast particles from solar flares. The distant termination shock and the subsonic flow beyond, with an eventual contact surface with the interstellar gas is another immediate inference. Someone coined the expressive term *heliosphere* for the entire structure. The occasional outbursts of fast dense wind from the Sun, causing geomagnetic storms and the Forbush cosmic-ray decrease, have the form of blast waves in interplanetary space (Parker, 1961). The fast streams of wind overtaking slow streams produce the spiral interplanetary interaction regions and are responsible for the 27-day recurring geomagnetic activity and cosmic-ray variations (Parker, 1963).

The direct *in situ* detection and quantitative study of the solar wind with instruments carried on spacecraft got underway about 4 years after the prediction of its general properties. The direct measurements in space (cf., Snyder and Neugebauer, 1962; Ness, Scearce, and Seek, 1964; Ness, Hundhausen and Bame, 1971; Hundhausen, 1972) verified its general nature and gave hard numbers for the highly variable velocity, density, temperature, and magnetic field. However, after forty years of study, it is ironic that the precise form of the heating of the expanding corona is not yet established. So it is still not possible to assert why the mathematical laws of physics require a star like the Sun to have a supersonic stellar wind. That one first link is still missing.

6. The X-Ray Corona

The intense X-ray emitting corona poses quite a different problem from the open corona that expands to form the solar wind. The energy requirement for heating the X-ray corona is some twenty times more intense. We must pay strict attention to the facts if we are to discover how it is done. The traditional idea about coronal heating, illustrating in principle how the convective zone might create a suprathermal atmosphere, is wave dissipation. For instance, it may be short period waves (period < 10 s) generated by the microflaring in and around the boundaries of the supergranules that heats the expanding corona (Martin, 1988; Porter and Moore, 1988), although it remains to be shown that there is a sufficient intensity of microflaring. In contrast with free expansion of the open corona, the X-ray coronal loops of 10^{10} atoms cm^{-3} are confined in the 10^2 G fields of bipolar active regions, and do not appear to be heated significantly by wave dissipation. The necessary energy input is about 10^7 ergs cm^{-2} s^{-1}, or twenty times the heat input to the expanding corona, far more than can be expected from microflaring, spicules, etc. Presumably the photospheric granules have enough power, with the characteristic convective energy transport rate $\rho\nu^3 \sim 2 \times 10^8$ ergs cm^{-2} s^{-1}. However, Alfvén waves are the only wave form expected to reach the corona from a photospheric source. The difficulty is that the enormous Alfvén speed C of about 2000 km s^{-1} in the bipolar magnetic fields provides a dynamical response time L/C of a magnetic loop of length L $(1 - 20 \times 10^4$ km$)$ in the range 5–100 s, whereas the dominant convective characteristic time is the granule turnover time of about 300 s or more.

Consequently the principal effect of the convection is a quasi-static shuffling and intermixing of the photospheric footpoints of the bipolar magnetic fields, at speeds of the order of the 1 km s^{-1} granule motions. The result is the gentle accumulation of twisting and interweaving of the field lines in the bipolar fields, rather than the generation of propagating waves (whose characteristic wavelength would be 6×10^5 km and greatly in excess of the typical length L of the bipolar fields). The twisting and interweaving introduces magnetic free energy which is then available for coronal heating, if there is a way to dissipate it. Resistive dissipation of the free energy is much too slow for interweaving on the granule scale $l \sim 500$ km. With $T = 2 \times 10^6$ K the resistive diffusion coefficient η is only about 10^3 cm^2 s^{-1}, so that the characteristic diffusion time l^2/η is of the order of 10^{12} s, or 3×10^4 yr. However, there is another macrophysical principle that enters here through the Maxwell stresses in the interwoven topology of the bipolar field. The essential point is that in any but very special field topologies the Maxwell stresses create surfaces of tangential discontinuity, i.e., current sheets, as the field relaxes to static equilibrium. The discontinuities are an essential part of the equilibrium. The random shuffling of the photospheric footpoints of the magnetic field generally does not provide the special topologies necessary to avoid the tangential discontinuities.

Now the nonvanishing resistive diffusion prevents the field from achieving the true discontinuity necessary for static equilibrium, so the Maxwell stress continually strives to achieve the discontinuity by displacing the fluid, and we recognize the process as the familiar rapid reconnection. It appears, then, that resistive instabilities, plasma turbulence, and anomalous resistivity in some form of rapid reconnection at the incipient surfaces of tangential discontinuity provide the dissipation of the magnetic free energy of the interwoven bipolar field. It is this process that seems to be the cause of the X-ray corona (Parker, 1972, 1983, 1994a).

The spontaneous appearance of tangential discontinuities in the static equilibrium of a magnetic field in an *infinitely* conducting fluid is not a familiar concept, although special cases are well known in association with the kink instability (cf., Rosenbluth, Dagazian, and Rutherford, 1979; Strauss and Otani, 1988). The theoretical basis for the discontinuities is the equation

$$\partial M_{ij}/\partial x_j = 0 \tag{15}$$

for the static equilibrium of the magnetic field in the absence of fluid pressure gradients. This condition is usually written in the form

$$\nabla \times \mathbf{B} = \alpha \mathbf{B} \ . \tag{16}$$

This is not a linear equation because α is itself a function of the field. The equation has the unfamiliar property of mixed characteristics. This may be seen by first examining the curl of the equation, which can be put in the form

$$\nabla^2 \mathbf{B} + \alpha^2 \mathbf{B} = \mathbf{B} \times \nabla \alpha \ . \tag{17}$$

The appearance of the Laplacian operator indicates two sets of complex characteristics. If there were nothing more, the equation would be fully elliptic, and specification of the field on the boundary of a region would uniquely determine the field throughout the interior. Discontinuities introduced at the boundary would not penetrate in to the interior, and the field would be continuous everywhere inside. This is the sort of static field equation with which we are familiar. However, if we take the divergence of Equation (16), the result is the equation

$$\mathbf{B} \cdot \nabla\alpha = 0 \tag{18}$$

for α. It is obvious by inspection that the field lines form a family of real characteristics. That is to say, α is constant on each field line, and specification of α on any one line places no restriction on α on any other line. So surfaces of tangential discontinuity are admissible. The equilibrium at the plane interface between two regions of uniform magnetic fields of equal strength and nonparallel direction is an elementary example of this condition. This is the unusual feature of a field equation with mixed characteristics. The necessity for the discontinuities becomes clear when we reflect that the continuous mapping of the footpoints of the field can produce any arbitrary interweaving of the field lines that we desire.

Imagine that we have a magnetic field extending through an infinitely conducting fluid from the boundary plane $z = 0$ to the boundary plane $z = L$. The footpoints of the field at $z = 0$ are held fixed while the footpoints at $z = L$ are intermixed in some arbitrary and complicated way with a continuous mapping. There are then flux bundles extending from $z = 0$ to $z = L$ that wind about the contiguous flux bundles first one way and then the other along the length L. Now if the field in any one flux bundle is to fit smoothly and continuously against the contiguous field around which it passes, the torsion α in the flux bundle must be carefully adjusted so that the field lines in the bundle are parallel to the contiguous field with which it is in contact. However, with the winding and wrapping, i.e., the topology, varying along the length of the flux bundle, there is no single fixed α along each line that can cause the field lines to be parallel everywhere along the length. The mathematics accommodates this dilemma by introducing surfaces of tangential discontinuity. The surfaces of discontinuity represent the surface of contact between regions of continuous field. Therefore they contain no magnetic field lines, and there is no restriction on the change in field direction from one side to the other. That it to say, Equation (18) has no application at the surface of discontinuity. So given the general restriction of Equation (18) on every field line, and given the fact the any arbitrary interweaving of the field lines can be accomplished by intermixing the footpoints of the field, there are necessarily discontinuities in the static equilibrium of almost all field line topologies.

There are, of course, infinitely many topologies which require no discontinuities. In our first primitive perturbation calculations we found (Parker, 1972) only the winding patterns that were invariant along the zero-order uniform field. Van Ballegooijn (1985) introduced a better expansion scheme and showed that the winding pattern may vary along the zero-order field in the same way that the vorticity varies with time in a two-dimensional flow of ideal inviscid fluid. The case that α has the same value on all field lines is another example (Rosner and Knobloch, 1982). However, such topologies are a set of measure zero compared to the field topologies that are produced by arbitrary continuous mapping of the foot points. In an attempt to disprove the possibility of tangential discontinuities, Field (1989) imagined that a surface of discontinuity has the topology of a single sheet and showed that this is inconsistent with the force-free conditions of equilibrium. His conclusion that there can be no surfaces of discontinuity is mistaken and his calculations can be used to demonstrate that the topology of the surfaces of discontinuity is far more complex, involving branching, etc., as is readily seen from the optical analogy (Parker, 1991, 1994a). Longcope and Strauss (1994) showed that the creation of a discontinuity involves a singularity in the internal mapping of the field lines, indicated by the Jacobian of the projection of the mapping along the field lines, from which they asserted that continuous mappings of the *footpoints* could not produce a discontinuity. They overlooked the fact that there is no fundamental objection to a discontinuous motion in an ideal fluid in the asymptotic relaxation to equilibrium. The discontinuity is an intrinsic part of the final static equilibrium, and there can be no equilibrium without the discontinuities in almost all cases. This is directly illustrated with the *optical analogy*. As with most dynamical systems, the relaxation to equilibrium may be only asymptotic in the limit of large t, so an asymptotic approach is not an objection to the concept that the Maxwell stresses push the fluid and field toward the creation of discontinuities in any final equilibrium.

The formal theory of the spontaneous formation of tangential discontinuities is most simply handled with the optical analogy, showing directly how the discontinuities are formed in response to local maxima in the field strength. In particular, the optical analogy illustrates the field topology associated with the surface of discontinuity. So once again we have a new macrophysical concept, that magnetic fields subject to continuous deformation at very large magnetic or Lundquist numbers tend toward internal surfaces of tangential discontinuity, across which rapid reconnection continues until the field topology is reduced to such simple form that discontinuities are no longer an essential part of static equilibrium. In the presence of continuing shuffling of the footpoints of the field, the reconnection never ceases. This principle seems to be the essential effect providing the dissipation of magnetic free energy that creates the X-ray corona of the Sun and similar stars. That is to say, it looks as though the spontaneous discontinuities are the basis for much of X-ray astronomy.

7. Conclusion

We suggest that the concept of macrophysics is useful in the approach to theoretical astrophysics, because many astronomical phenomena are a result of physical effects that cannot be demonstrated in the restricted scales of the terrestrial laboratory. The macrophysical principles associated with an astronomical phenomenon come to light when enough observational facts are assembled to constrain the problem in some suitably precise way. A couple of recent examples have been cited by way of illustration. It is important to recognize when conventional physical principles and ideas do not explain an observed phenomenon, because the comfortable acceptance of a problem as solved when in fact it is not, obscures the truly novel features of so many astronomical happenings. Thus, as already noted, the observations must have enough detail to show what is not the explanation, and a primary function of any theoretical investigation is to make hard-headed estimates of the existing explanations. Too often such critical quantitative estimates are conspicuously absent from theoretical papers. Having decided that there is no viable existing explanation, one proceeds with due attention to the observational constraints and to the basic equations and concepts of physics to hunt for, invent, or otherwise stumble across the novel macrophysical principle embodied in the particular phenomenon. However, we can succeed in this activity only if we are willing to accept unfamiliar concepts when the evidence leads us to them. In both cases reviewed here the simple but unfamiliar concepts were widely rejected for extended periods. It was as if everything worth knowing was already known, so that an expert in the field knew that something new cannot be correct. In fact, macrophysics is far more interesting than this common view would allow, with many concepts or principles yet to discovered by the inquiring mind. There is every reason to expect that the rapid advance of observational knowledge will provide enough constraints to allow formulation of some of the outstanding puzzles presented by the Sun. From there some hard thinking should lead to the next advances in macrophysics. We should all be looking forward to such occasions, however harshly new principles may grate on our sensibilities.

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