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SPACE PHYSICS BEFORE THE SPACE AGE

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Today, in the space age, the term "solar wind" is a scientific byword and not entirely unknown to the daily newspapers. However, it must be appreciated that, prior to our ability to carry out scientific observations in space, the concept developed only very slowly from the days of Galileo and Newton. The subject was pursued through the physics of the active geomagnetic field, the physics of the solar corona, and the physics of cosmic rays and comet tails.

The corona is conspicuous during an eclipse of the Sun, but its true nature as a million degree atmosphere was not realized until the ingenious laboratory detective work of Grotrian (1939) and Edlén (1942), who extrapolated along isoelectronic ionic series to establish the energy levels of Fe X, Fe XI, Ca XV, etc., from which the coronal forbidden lines in the visible range could be identified. It was a laborious and highly technical task, and they were gambling that the explanation for the strange coronal emission lines lay in extraordinarily high temperature (already suggested by the observed scale height and thermal radio emission). The result was a fundamental advance in the physics of stars, for who could have guessed that the outer atmosphere of a pedestrian star like the Sun would be heated to X-ray temperatures? The obvious challenge is to understand the physics behind this remarkable suprathermal phenomenon.

If we turn to the activity in the terrestrial atmosphere and magnetic field, the aurora is visible to all who live at middle and high latitudes. On the other hand, geomagnetic fluctuations are not so conspicuous and were discovered by Graham (1724) and Celsius (1741) by observing a compass needle with a microscope. It is interesting to note that de Mairan (1754) proposed that both the aurora and the geomagnetic fluctuations are a consequence of solar particles entering the terrestrial atmosphere, based on the mistaken idea that the zodiacal light represents the extended corona of the Sun.

Once Schwabe had established the sunspot cycle (see von Humboldt 1858, p. 49), Sabine (1852) pointed out the close tracking of the geomagnetic fluctuations. Broun (1858, 1874) noted the 4 week recurrence of magnetic activity, and Maunder (1904, 1905, 1916) showed that the recurrence represents the 27 day rotation of the Sun, as viewed from the orbiting Earth. So the Sun was clearly identified as the driver of geomagnetic activity.

The association of geomagnetic activity with solar brightenings (white-light flares) was first noted in 1858 (Carrington 1859; Hodgson 1859). The brightenings were more effectively observed with the inventions of the spectroheliograph and spectrohelioscope, beginning in 1892 (Deslandres 1910; Hale 1929). It was soon noticed that geomagnetic and auroral events often follow a couple of days after intense flares on the Sun, indicating the ejection of particles from the Sun at 10^3 km s^{-1}.

Dalton (1793) and Gauss (1839) suggested that the aurora is an electrical phenomenon, and Fitzgerald, prior to 1900, pointed out the similar appearance of auroral filaments and the cathode-ray streamers in the laboratory Crookes tube. Birkeland (1896) proposed that the Sun emits electrons (which were in the process of being discovered and defined at that time) and developed his celebrated terrella experiment, with the Sun as the cathode and Earth as the anode of a "celestial" Crookes tube. It was impressive to see that his apparatus exhibited the convergence of the incident electrons into a thin zone around the north and south polar regions of his magnetized model of Earth. He noted, too, that the perturbation of the dipole magnetic field of his model of Earth resembled the geomagnetic storm fluctuations.

Störmer (1955) was motivated by Birkeland's work to devote the next several decades to computing the trajectories of charged particles in a dipole magnetic field. Schuster (1911) pointed out that the large total charge in the postulated electron beam from the Sun would disperse the beam. Lindeman (1919) proposed, therefore, that the particle beam must be electrically neutral and made up of equal numbers of electrons and protons. The inclusion of protons was an important step because the mass of the proton is large enough to provide significant momentum and energy (5 keV) at the conjectured speeds of 10^3 km s^{-1}. Somewhere along the way, these isolated beams of particles began to be called "solar corpuscular radiation."

Chapman & Ferraro (1931, 1932, 1933) showed how the impact of a beam of electrons and protons would compress the geomagnetic field to produce the onset of a geomagnetic storm. Some years later, Simpson (1954; Meyer, Parker, & Simpson 1957) studied the energy spectrum of cosmic-ray variations and showed that the variations cannot be the result simply of changes in the geomagnetic cutoff energies or of electrostatic fields in a hard vacuum, as was then popularly believed, concluding that the variations can be produced only by magnetic fields in interplanetary space, manipulated presumably by solar corpuscular radiation. Biermann's (1957) inference, that the antisolar acceleration of comet tails can be understood only as a consequence of the impact of solar corpuscular radiation, led him to the startling realization that the Sun emits solar corpuscular radiation in all directions at all times, regardless of whether the Sun is active or quiet. This, along with Simpson's work, was the basic step away from the traditional idea that space is a hard vacuum except for well-defined beams of solar corpuscular radiation. It showed, too, that the creation of solar corpuscular radiation is carried on irrespective of magnetic active regions on the Sun.

Then Chapman (1959) showed the remarkable fact that the enormous thermal conductivity (Chapman 1954), weak thermal emission, and million degree temperature of the solar corona extend the coronal gas far out into space, beyond the orbit of Earth. De Mairan (1754) had not been entirely wrong in his earlier conjecture.

This was the state of knowledge by 1957, although relatively little attention was paid to these fundamental revelations of Biermann and Chapman at the time. I was fortunate to have the opportunity to discuss these ideas with both Biermann and Chapman, and I came away with the impression that there was no basis for doubting the conclusions of either. However, after some thought, it became clear that Chapman's extended corona would not permit the free passage of the solar corpuscular radiation required by Biermann because the two-stream plasma

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instability would lock the two together. After further thought, I realized that the only reconciliation of the two concepts would be to suppose that Chapman's static corona near the Sun somehow becomes Biermann's solar corpuscular radiation at large distances. However, it was not clear at that time how to treat the dynamics of either the tenuous solar corona or the solar corpuscular radiation.

Both Chapman's extended corona and Biermann's solar corpuscular radiation represent electrically neutral, essentially collisionless, magnetized plasmas. Thus, any large-scale motion represents the mean of the complicated gyrations of the ions and electrons about the inhomogeneous magnetic field. Then the electric currents required by Ampere's law must be provided somehow. These considerations so confused the problem that it was not immediately obvious how to treat the bulk motion of the plasma and the associated magnetic field. The direct approach was to sum over all the individual particle motions (described in the guiding center approximation). Carrying out this exercise showed that (1) the local particle gyrations automatically provide precisely the electric current across the field required by Ampere, (2) the magnetic field variations are described by the familiar MHD induction equation, and (3) the bulk motion is described by the MHD momentum equation in which the particle pressures parallel and perpendicular to the field are not necessarily equal (Parker 1957). Once these basic principles were established, it was clear how to proceed with the dynamics of the solar corona.

The mathematical solution of the steady ($\partial/\partial t = 0$) radial momentum equation for an extended coronal temperature (represented by the idealized case of a uniform temperature) was out of the ordinary but quite simple (Parker 1958a). There was the expected infinite family of solutions, but there was one (and only one) solution that satisfied the requirements that the gas be dense, quasi-static, and strongly bound gravitationally at the Sun at the same time that the gas pressure falls to zero at infinity. That solution showed how Chapman's quasi-static corona near the Sun gradually accelerates outward, crossing the sonic point at a distance of several solar radii and becoming Biermann's supersonic solar corpuscular radiation at large distance. The essential point was that the dynamical state of a hot tenuous atmosphere, strongly bound gravitationally at its base but with an extended temperature, is not stasis but rather a gradual steady outward acceleration to supersonic velocity at large distance. The principle applies on all scales from planets to stars to galaxies. Applied to the Sun, the principle immediately spelled out the main features of the expanding plasma and magnetic field throughout interplanetary space. The weak magnetic fields in the expanding solar corona are stretched outward into an Archimedean spiral pattern, automatically sweeping away the lower energy Galactic cosmic-ray particles. There is obviously a variety of internal dynamical structures, including blast waves from coronal transients, interplanetary interaction regions between fast and slow winds at different heliocentric longitudes, the impact against the planetary magnetospheres, the terminal shock at the outer reaches, etc. (Parker 1958b, 1963, 1965; Dessler & Parker 1959). The expanding corona automatically sweeps the interstellar gas and magnetic field out of the solar system, to distances on the general order of 10^2 AU. The solar wind was the obvious term for the supersonic expansion, emphasizing the purely hydrodynamic origin at the Sun. The general form of the active interplanetary environment was finally spelled out.

The space age soon stepped in to provide overall verification and precise measurements, along with the exciting discovery of the many special features that could not be anticipated by the basic theory.

So it has been a long road from the eighteenth century, and there are still some miles to go now in the space age. In particular, we must not overlook the fact that the heat source that creates the extended temperature of the expanding corona remains a matter of conjecture. Until that issue is firmly resolved, it is not possible to state why the Sun is compelled by the laws of nature to possess a supersonic solar wind.

REFERENCES

Biermann, L. 1957, Observatory, 77, 109
Birkeland, K. 1896, Arch. Sci. Phys. Nat. Geneva, June
Broun, J. A. 1858, Philos. Mag. 16, 81
———. 1874, CR Acad. Sci. Paris, 76, 695
Carrington, B. C. 1859, MNRAS, 20, 13
Celsius, A. 1741, Svensk Vetensk. Acad. Handl., 1, 391
Chapman, S. 1954, ApJ, 120, 151
———. 1959, Proc. R. Soc. London A, 253, 452
Chapman, S., & Ferraro, V. C. A. 1931, Terr. Magn. Atmos. Elec., 36, 77
———. 1932, Terr. Magn. Atmos. Elec., 37, 147
———. 1933, Terr. Magn. Atmos. Elec., 38, 79
Dalton, J. 1793, Meteorological Observations and Essays (1st ed.; London: Ostell)
de Mairan, J. J. d'O. 1754, Suites Mem. Acad. R. Sci. Paris, 2d ed.
Deslandres, H. 1910, Ann. Meudon Obs., 4, No. 1
Dessler, A. J., & Parker, E. N. 1959, J. Geophys. Res., 64, 2239
Edlén, B. 1942, Z. Astrophys., 22, 30
Gauss, C. F. 1839, Resultate aus den Beobachtungen des magnetischen Vereins im Jahre 1838
Graham, G. 1724, Philos. Trans. R. Soc. London, A, 32, 96
Grotrian, W. 1939, Naturwissenschaften, 27, 214
Hale, G. E. 1929, ApJ, 70, 265
Hodgson, R. 1859, MNRAS, 20, 15
Lindeman, F. A. 1919, Phil. Mag., 38, 669
Maunder, E. W. 1904, MNRAS (Geophys. Suppl.), 64, 205
———. 1905, MNRAS (Geophys. Suppl.), 65, 2
———. 1916, MNRAS (Geophys. Suppl.), 76, 63
Meyer, P., Parker, E. N., & Simpson, J. A. 1957, Phys. Rev., 104, 768
Parker, E. N. 1957, Phys. Rev., 107, 830
———. 1958a, ApJ, 128, 664
———. 1958b, Phys. Fluids, 1, 171
———. 1963, Interplanetary Dynamical Processes (New York: Wiley-Interscience)
———. 1965, Space Sci. Rev., 4, 666
Sabine, E. 1852, Philos. Trans. R. Soc. London, A, 142, 103
Schuster, A. 1911, Proc. R. Soc. London A, 85, 44
Simpson, J. A. 1954, Phys. Rev., 94, 427
Störmer, C. 1955, The Polar Aurora (Oxford: Clarendon)
von Humboldt, A. 1858, Cosmos (English transl. by E. C. Otte, W. S. Dallas, & B. H. Paul; London: Bohn)

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