GEOACTA, 20, 1 - 10, 1993

EVOLUTION OF THE FLUID MODELS FOR THE SOLAR CORONAL EXPANSION

P. Alexander

Departamento de Física, Facultad de Ciencias Exactas y Naturales
Universidad de Buenos Aires
Buenos Aires, Argentina

Abstract

The question of just how the solar corona is expanding into the surrounding interplanetary region has been one of the most striking topics of space science since the late 1950's and it is still far from a definitive answer. The present script gives an overview of the observations and theories that led to the concept of that expansion and describes the subsequent models up to the present time. Finally, some of the open questions on the phenomenon are mentioned.

Resumen

El interrogante acerca de cómo la corona solar se expande hacia la región interplanetaria circundante ha sido uno de los temas más apasionantes de la ciencia espacial desde fines de la década del '50 y está aún lejos de una respuesta definitiva. El presente escrito hace una revisióm de las observaciones y teorías que condujeron al concepto de esa expansión y describe los modelos subsiguientes hasta la actualidad. Finalmente se mencionan algunos de los interrogantes abiertos de este fenómeno.

1. Introduction

The solar corona is the outer shell of the Sun's atmosphere and has traditionally been observed at the time of solar eclipse. The fluid in this zone is so hot (1-2 x 10^6 K) that even the Sun's enormous gravity can no longer retain it and a continuous outflow of mass, called the ``solar wind", fills the interplanetary region. Electrons and protons are the major constituents of this gas.

It is wellknown that the Sun is the Earth's main source of energy. Although the energy the Sun puts into release of the solar wind is about one millionth of the amount given off through the electromagnetic radiation, some phenomena such as geomagnetic storms and aurorae show that the first also plays an important role in determining the evolution of the Earth system. The study of the solar wind may not only improve the understanding of the variable conditions in our planet, but also broaden the knowledge on plasma theory, astronomy, space physics, geophysics and other areas.

This paper is an extension of a previous publication (Alexander 1992a) on the history of the study of the solar coronal expansion. There is no intention of providing an encyclopedic survey of everything that has been done in the field; some but by no means all of the relevant literature will be cited in this script. The classification in periods is by importance rather than by the date the works were performed. The next section gives an overview on the progress of knowledge, theories and observations related to the solar coronal expansion, up to the appearance of the first fluid models for this phenomenon. The following two sections show the details of the evolution of the original fluid models up to nowadays, according to the constrictions imposed by the increasing number of satellitary observations. The concluding section exhibits some open questions on the solar wind.

2. The Prehistory

An early reference to the absence of vacuum around the Sun may be found in Cassini's (1672) (see fig. 1) theory that dust particles scatter the zodiacal light. Cometary studies during the first half of the nineteenth century were concerned with an interplanetary resisting medium in relationship with the form of comet tails and in agreement with Newton's ideas of the ether (see e.g. Bessel 1836). During the second half of that century Sabine (1852) suggested the existence of a connection between the sunspots and magnetic fluctuations on the Earth, and the observation that some transient and intense solar phenomena were followed by the appearance of geomagnetic storms and aurorae some hours later also led to a cause-effect link between solar activity and terrestrial events (see e.g. Carrington 1860). These facts provided the motivation for many studies on the probable gas emission from the Sun, including those of Fitzgerald (1892) and Milne (1926), and its effects on the geomagnetic field (see e.g. Chapman 1919, Chapman and Ferraro 1931, 1933). These ideas were initially rejected, among others by Kelvin (1892), but they slowly gained recognition during the first half of the present century.

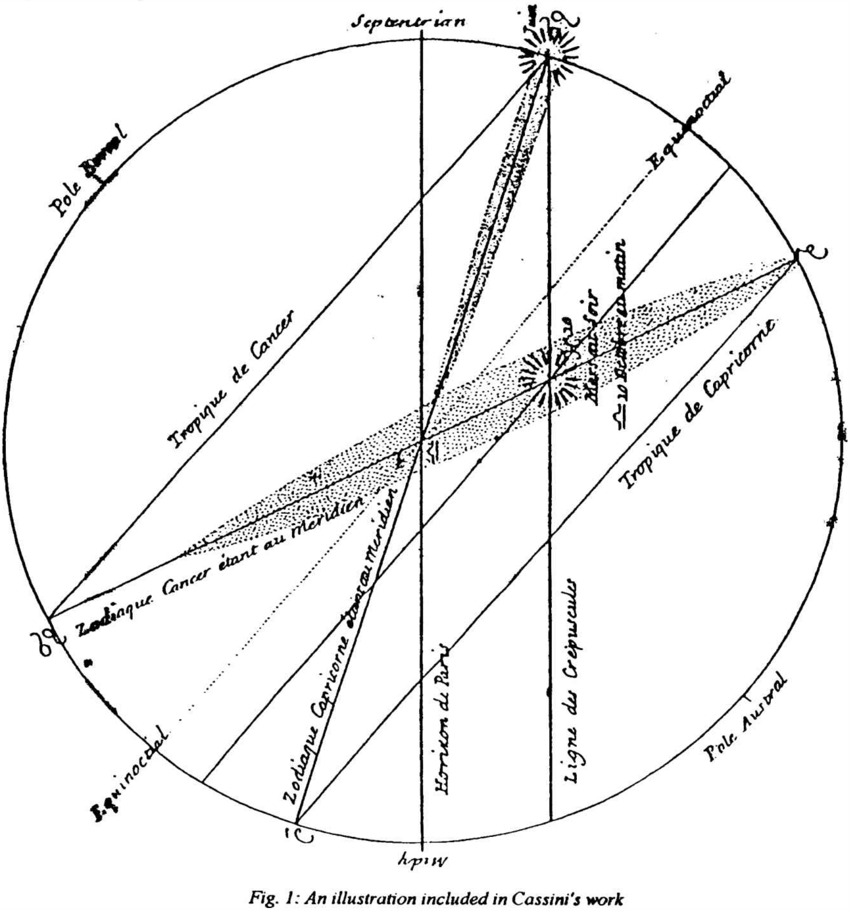

Fig. 1: An illustration included in Cassini's work

New observational evidence for the nuous presence of an interplanetary gaseous mediun was exhibited during the 1950's. The cal light was found to be strongly polarized. It was suggested (Behr and Siedentopf 1953) tl ch an effect was produced by scattering from electrons with a density of 1000 cm^{-3} near the E orbit. Nowadays scattering from particulate matter is held to produce the zodiacal light and i larization, and observations yield electron densities of the order of 10 per cm^3 near the Eartl other interesting fact was the decrease in cosmic-ray intensity following sunspot activity ol ed by Forbush (1954). This phenomenon could be explained if the Earth was enveloped b asma cloud ejected from the Sun as a consequence of that activity because the surrounding m ic field would prevent the cosmic-rays from reaching our planet (Morrison 1956). The whistle ervations (Helliwell and Morgan 1959) also confirmed these ideas and suggested electron densi of a few 100 per cm^3 at distances of 4 Earth radii. We now know that such a position refers to Earth's magnetosphere, but at that time such numbers agreed with other measurements.

Some researchers had previously in ced but did not deepen the ideas of an interaction of ``corpuscular radiation" with comet tails ffmeister 1943) and of an interrelation between ``solar particle radiation" and the recurrence of in types of geomagnetic activity (Bartels 1939). These papers were the supports for the burial c view of a discrete flow of particles through a vacuum: Biermann (1951, 1953, 1957) was the t who suggested a continuous outflow of gas in all directions in his explanation of the pers t antisolar orientation of comet tails, and that concept established the base for most of the com: nodels. By the way, the solar wind-comet interaction is now known to be different from that pro l by Biermann at that time.

3. The History

The evidence for mass ejection wa: errupted by Chapman (1957), when he considered a hydrostatic model (the corona and its e sions stayed at rest). It was assumed that energy was transferred only by heat conduction, all r fluxes being negligible. The equations for the plasma were:

$$\frac{dP}{dr} + \frac{G m_s m_p N}{r^2} = 0 \tag{1}$$

$$\frac{d}{dr}(r^2 Q) = 0 \tag{2}$$

$$P = 2NkT \tag{3}$$

$$Q = -k_o T^{5/2} \frac{dT}{dr} \tag{4}$$

where P is the total pressure of electr and protons, G the gravitational constant, m_s the mass of the Sun, m_p the proton mass, N the de ty of either species (neutrality is assumed to be valid), r the heliocentric distance, Q the heat flu tensity (of the electrons because the contribution of the ions is negligible in the solar wind), k Boltzmann's constant, T the temperature for electrons or protons (the collisions ensure the equality) and k_o is a weak function of N and T and therefore it is considered to be a constant (Chapman estimated for the solar wind a value of the order of 5.2 x 10^{-7} erg cm^{-1} sec^{-1} $K^{-7/2}$). Equation (1) expresses the hydrostatic equilibrium, (2) represents the conservation of energy, (3) shows that the equation of state for an ideal gas is assumed to be valid and (4) is the Spitzer and Härm (1953) formula for a radial heat flux. The sationary state and the spherical symmetry have been considered in the first two equations.

Chapman's model was accepted because the calculated density at 1 AU (one astronomical unit = Sun-Earth mean distance = 1.5 x 10^8 km) was compatible with the values inferred from whistler, zodiacal light and comet observations (all of them of the order of 500 cm^{-3}). This model leads to a difficulty at large heliocentric distances (as will be explained in the next paragraph). Nonetheless, its importance rests on the fact that it showed that the corona could not terminate near the Sun.

Parker (1958a) examined Chapman's model and found that the pressure remained finite as $r \rightarrow \infty$ and was large in comparison with any reasonable estimate of interstellar pressure which might be invoked for balance. Inclusion of loss mechanisms (e.g. radiation) did not provide a satisfactory resolution of the problem, and as Parker was aware of Biermann's papers he concluded that the corona must expand. He proposed the following hydrodynamic model:

$$\frac{d}{dr}(r^2 N U_r) = 0 \tag{5}$$

$$m_p N U_r \frac{dU_r}{dr} = -\frac{dP}{dr} - \frac{G m_s m_p N}{r^2} \tag{6}$$

where U_r is the fluid's mean radial velocity as measured from the Sun. Notice that (5) is the continuity equation and (6) is the radial component of the equation of motion, both for a steady-state, spherically symmetric flow. The equation of state (3) was also included and the need for an energy equation like (2) was avoided by the inclusion of a given outline for the temperature: constant up to some distance and null (because thermal conduction is negligible when compared with the other energy fluxes) from there on. He also computed the magnetic field and predicted an interplanetary spiral configuration.

Parker obtained analytical solutions. The results reproduced the velocities required by Biermann's work, the calculated densities at 1 AU were in agreement with the accepted values at that time and $P \rightarrow 0$ as $r \rightarrow \infty$. The outflow of mass, termed by Parker (1958b) the solar wind, was a necessary consequence of the high temperature of the corona. In the following years Parker (e.g. 1963, 1964, 1965) introduced some additional ideas into his model, for example the inclusion of an energy equation.

For some time the existence of the solar wind was involved in controversy. An important support was provided by the first in situ measurements made in 1959 by the Soviets with spaceships Lunik III and Venus I (Gringauz et al 1960) and in 1961 by the Americans with spacecraft Explorer 10 (Bonetti et al 1963). A notable program performed on the Mariner 2 space probe in 1962 removed any possible doubts as to the existence and composition of the continuous solar wind (Neugebauer and Snyder 1962). The observed velocities and densities were in agreement with the values obtained by the previous spacecrafts (about 300 km/sec and 5 cm^{-3}). In the years following

1962 the interplanetary magnetic field configuration was found to fit Parker's description.

The objections to the hydrodynamic model continued for some time. Chamberlain (1960) considered an evaporative model of the corona that determined a critical level above which coronal ions would move outward from the Sun with no further collisions. In this solar ``exosphere" the motion of individual ions in the gravitational and electric field were followed and mean properties deduced as a function of heliocentric distance. The mean speed of the ions at 1 AU was found to be 10 km/sec, so that this ``solar breeze" model was considered to be unrealistic after some years of measurements. Some later exospheric models (for example Brandt and Casinelli 1966, Jockers 1970) significantly reduced the discrepancy with observations. Nevertheless, the models based on Parker's ideas provided more appropriate descriptions. The analysis of the measurements also suggested a hydrodynamic behaviour.

Why may hydrodynamic models be appropriate to describe the solar coronal expansion? The assumption underlying this concept is that the mean free path is small near the Sun, and at other places the interplanetary magnetic field causes the particles to interact indirectly so that the medium still behaves as a conventional fluid even if there are essentially no collisions (see e.g. Dessler 1967). An important theoretical support for the idea that a strong magnetic field can cause a plasma to be described as a hydrodynamic system even if collisions are rare was developed by Alfvén (1950).

Since Parker's original paper, two different points of view have been adopted to obtain a complete set of equations for the solar plasma: the macroscopic description (hydrodynamics, fluids) and the microscopic description (kinetics, statistics). The equation sets derived with either framework are not complete, because every equation includes a variable that is also determined by the next equation of the hierarchy. The continuity equation (5) includes the density and the velocity, the evolution of the last one also being given by the equation of motion (6), but this last expression contains the pressure so that the energy equation is needed, which may include the pressure (this magnitude is not present in Chapman's energy equation because he neglected the thermal energy) but also introduces the heat flow, etc.. A closure relationship has to be used to break this chain at some step.

Most models developed after Parker's original idea were based on his equation set. Usually they included the three basic hydrodynamic equations, i.e. continuity, motion and energy (it may be more than one energy equation if thermal anisotropy or different temperatures for each species are considered) and the heat flow equation in terms of the other magnitudes (the closure relationship). Chamberlain (1961) was the first author that included all these equations and obtained a solution from them. Two of Maxwell's equations, Gauss' law for the magnetic field and the Faraday-Henry law (for a fluid with a high electrical conductivity), were usually used to find the magnetic field. After the application of the steady-state and spherical symmetry conditions in an inertial frame of reference fixed to the Sun they yield

$$\frac{d}{dr}(r^2 B_r) = 0 \qquad (7)$$

$$\frac{d}{dr}[r(U_r B_\phi - U_\phi B_r)] = 0 \qquad (8)$$

where B_r and B_ϕ refer to the radial and azimuthal magnetic field components U_ϕ is the azimuthal velocity. Some authors replaced the last equation by

$$\frac{U_\phi - \omega r}{U_r} = \frac{B_\phi}{B_r} \tag{9}$$

where ω is the angular speed of the Sun. It can be shown that (8) and (9) are equivalent for the solar wind (Weber and Davis 1967). Parker used (7) and a simplified version of (9) in his initial equation set.

The topology of the solutions of the models following Parker's idea was similar: a transition from subsonic to supersonic flow near the Sun, $P \to 0$ as $r \to \infty$, $B_r \sim r^{-2}$, etc.. In order to reduce even more the gap between predictions and observations, mainly in the equatorial plane of the Sun at 1 AU (where most data come from), the successive papers aimed to use more complex equation systems, which required numerical solution. The most significant differences in the results of these schemes were related to the expressions used for the energy equation and the closure relation and the treatment of the magnetic field.

Energy equations assuming the steady-state and the spherical symmetry, like the one used by Noble and Scarf (1963)

$$\frac{d}{dr}\left[r^2\left(\frac{N m_p U_r^3}{2} + \frac{5 P U_r}{2} + Q\right)\right] + \frac{U_r G m_s m_p N}{r^2} = 0 \tag{10}$$

included not only the heat, as in equation (2), but also the kinetic, thermal, and gravitational terms. Some models also introduced energy exchange terms between both species (e.g. Hartle and Sturrock 1968, Cuperman and Harten 1970, Toichi 1971) or dissipation of hydromagnetic waves (for example Barnes 1969, Hung and Barnes 1973). The relevance of the last two concepts to the corona remains debatable.

Regarding the closure relation, two paths have been taken. One way cuts the chain of the hierarchy at the equation of motion, which means that either the temperature is a given function of the other variables, as considered for example by Parker (1958a) with his isothermal-like description, or that the same holds for the pressure, as applied for example by Weber and Davis (1967) with the polytropic law

$$\frac{P}{\rho^\gamma} = \text{constant} \tag{11}$$

where ρ is the mass density of the gas and γ is the polytropic index (found from theory or measurements). The other way interrupts the chain with the energy equation, which implies that the heat flow **Q** will be expressed in terms of the other physical magnitudes. Some examples, as considered respectively by Parker (1964), Wolff et al (1971), Hollweg (1976) are:

$$\mathbf{Q} = -k_o T^{5/2} \nabla_r T \tag{12}$$

$$\mathbf{Q} = -k_o T^{5/2} \nabla_{\parallel} T \tag{13}$$

$$\mathbf{Q} = \frac{3}{2} NkT_e(\mathbf{U} - \Omega \times \mathbf{r})\alpha \tag{14}$$

where ∇_r is the radial gradient, $\nabla_{\parallel}$ the gradient parallel to the magnetic field, T_e the electron temperature, **U** the bulk velocity of the fluid, Ω the angular velocity of the Sun, **r** the heliocentric position and α a factor that depends on the electron velocity distribution function. The source of the first two equations is the paper by Spitzer and Härm (1953) and the third equation was derived by Hollweg in his paper.

The hydrodynamic description of collisionless plasmas in strong magnetic fields and the inclusion of magnetic field **B** not only in (7) and (8), but also in the equation of motion through the term

$$\frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi}$$

gave birth to the MHD (magnetohydrodynamic) models of the solar wind. Notice that the magnetic force term is not included in (6). The azimuthal component of the equation of motion shows now that the angular momentum is carried not only in azimuthal particle motions but also in the azimuthal magnetic stresses. Weber and Davis (1967) closed the system with a polytrope and achieved similar results to Parker's original model. Later on, the energy equations also included the term

$$\frac{B^2}{4\pi}$$

and the corresponding solutions led to larger values for the speed at 1 AU, which was even in better agreement with observations (see e.g. Brandt et al 1969, Whang 1971). A remarkable consequence of the inclusion of the new terms was the increased complexity of the resolution because the magnetic field had to be found in a selfconsistent way with the other variables instead of being independently calculated at the end of the process, so that an important help in the search for numerical solutions has been provided by the steeply increasing power of computers in the last decades.

More variables were included in some developments. The two-fluid models (e.g. Sturrock and Hartle 1966, Cuperman and Harten 1970) argued that the collision frequency was very low in almost all the heliosphere and introduced different temperatures T_e and T_p for electrons and protons. The equation of state (3) had to be replaced by

$$P = Nk(T_e + T_p) \tag{15}$$

Incorporation of this effect left the continuity equation (5) unchanged and required the use of (15) in the momentum equation. However, separate energy equations had then to be written for each species. Other models included the thermal anisotropy (e.g. Weber and Davis 1970, Hollweg 1971, Marsch and Richter 1987), which is originated not only by the low collision frequency beyond some heliocentric distance, but also by the privileged direction introduced by the magnetic field. The last change, which gave rise to a tensor for the pressure, also affected the equation of motion, and one equation of energy was needed for each thermal component of electrons and protons. Studies of the role played by viscosity have been undertaken by several investigators (among others Scarf and Noble 1965, Weber and Davis 1970, Wolff et al 1971) and this concept has been finally discarded for the solar wind.

4. The Modern Age

Based on lessons learned from model studies and observational data, solar wind models appeared to converge in the direction of a two-region concept: near the Sun the solar wind is one-fluid and thermally isotropic, whereas at large heliocentric distances the plasma becomes collisionless, which implies that the electrons and protons have different temperatures and that the protons become thermally anisotropic (see e.g. Burlaga 1971, Leer and Holzer 1972, Acuña and Whang 1976, Alexander 1992b). The position of the transition zone is a few tenths of solar radii away from the Sun's surface. Some authors have concluded that there is a need for three-dimensional and time-dependent solar wind models (see e.g. Fahr and Fichtner 1991).

Asking for the ``average" solar wind may be meaningless. It seems reasonable that one criterion for sorting the solar wind into categories should be the bulk speed. Low- and high-speed streams might be essentially different phenomena and might result from different conditions in the corona. For a long time theorists have thought in terms of a ``quiet" wind and believed to find it represented in the ``slow" wind (for references see Hundhausen 1972), because the models fit the experimentally determined numbers for the low-speed wind much better. Other authors (see e.g. Feldman et al 1976) suggested that the quiet wind is more likely to be found in the ``fast" wind, i.e. in the high-speed streams occurring predominantly a few years before sunspot minimum.

The evolution of the low-speed wind is not an issue because, as just stated, predictions of MHD models are generally consistent with measurements. The differences between theory and observations are more appreciable for the high-speed wind (Neugebauer 1991) and there is no shortage of suggestions about the mechanisms responsible for its behaviour: wave acceleration, suprathermal electron heat flux and small-scale sources of momentum and energy (see e.g. Whang and Chien 1978, Pneuman 1986, Chuan-Yi Tu 1987).

5. Open Questions

We are far from consensus or from agreement between predictions and measurements on many points. The relative contributions of diverse mechanisms to the high-speed flow have to be determined. The models for the slow wind still yield to low values for the azimuthal speed at 1 AU. It is also desirable to find an appropriate description of the electron heat conduction for the distant collisionless solar wind because the classical Spitzer-Härm conductivity represents an inadequate expression for that fluid (see e.g. Scudder and Olbert 1983). Measurements at short and large distances from the Sun are needed because the tests of the solutions at 1 AU are not sufficient to give definite answers about the validity of the models (see Barnes 1992). These problems show that probably even more sophisticated equation sets must still be developed.

References

- Acuña, M. and Whang, Y.C.: A two-region model of the solar wind including azimuthal velocity, Astrophys. J., 203, 720 (1976)
- Alexander, P.: Historical perspectives on the study of the solar coronal expansion, Eos, 73, 433 (1992a)
- Alexander, P.: Una descripción magnetohidrodinámica de la expansión de la corona solar, Tesis de Doctorado, Universidad de Buenos Aires (1992b)
- Alfvén, H.: Cosmical Electrodynamics, Clarendon Press, Oxford (1950)
- Barnes, A.: Collisionless heating of the solar wind plasma. II. Application of the theory of plasma heating by hydromagnetic waves, Astrophys. J., 155, 311 (1969)
- Barnes, A.: Acceleration of the solar wind, Rev. Geophys., 30, 43 (1992)
- Bartels, J.: Geomagnetic and solar data, J. Geophys. Res., 54, 296 (1949)
- Behr, A. and Siedentopf, H.: Untersuchungen über Zodiakallicht und Gegenschein nach lichtelektrischen Messungen auf dem Jungfraujoch, Zeitsch. Astrophys., 32, 19 (1953)
- Bessel, F.W.: Beobachtungen über die physische Beschaffenheit des Halley'schen Kometen, Astron. Nachr., 13, 185 (1836)
- Biermann, L.: Kometenschweife und solare Korpuskularstrahlung, Zeitsch. Astrophys., 29, 274 (1951)
- Biermann, L.: Physical processes in comet tails and their relation to solar activity, Mem. Soc. Sci. Liège, 13, 251 (1953)
- Biermann, L.: Solar corpuscular radiation and the interplanetary gas, Observatory, 77, 109 (1957)
- Bonetti, A., Bridge, H.S., Lazarus, A.J., Lyon, E.F., Rossi, R. and Scherb, F.: Explorer 10 plasma measurements, J. Geophys. Res., 68, 4017 (1963)
- Brandt, J.C. and Cassinelli, J.P.: Interplanetary gas XI. An exospheric model of the solar wind, Icarus, 5, 47 (1966)
- Brandt, J.C., Wolff, C. and Cassinelli, J.P.: Interplanetary gas XVI. A calculation of the angular momentum of the solar wind, Astrophys. J., 156, 1117 (1969)
- Burlaga, L.F.: The Solar Envelope, NASA-GSFC, Greenbelt (1971)
- Carrington, R.C.: Description of a singular appearance seen in the Sun on September 1, 1859, Month. Not. R. Astron. Soc., 20, 13 (1860)
- Cassini, J.D.: Découverte de la lumiere celeste que paroist dans le zodiaque, Mem. Acad. Sci. (Paris), 8, 121 (1666-1699)
- Chamberlain, J.W.: Interplanetary gas II. Expansion of a model solar corona, Astrophys. J., 131, 45 (1960)
- Chamberlain, J.W.: Interplanetary gas III. A hydrodynamic model of the corona, Astrophys. J., 133, 675 (1961)
- Chapman, S.: An outline of a theory of magnetic storms, Proc. R. Soc. (London), A95, 61 (1919)
- Chapman, S. and Ferraro, V.C.A.: Theory off magnetic storms, Terr. Magn Atmos. Elect., 36, 77 (1931)
- Chapman, S. and Ferraro, V.C.A.: New theory of magnetic storms, Terr. Magn. Atmos. Elect., 38, 79 (1933)
- Chapman, S.: Notes on the solar corona and the terrestrial ionosphere, Smithsonian Contrib. Astrophys., 2, 1 (1957)
- Chuan-Yi Tu: A solar wind model with the power spectrum of alfvénic fluctuations, Solar Phys., 109, 149 (1987)
- Cuperman, S. and Harten, A.: Noncollisional coupling between the electron and proton components in the two-fluid model of the solar wind, Astrophys. J., 162, 315 (1970)
- Dessler, A.J.: Solar wind and interplanetary magnetic field, Rev. Geophys., 5, 1 (1967)
- Fahr, H.J. and Fichtner, H.: Physical reasons and consequences of a three-dimensionally structured heliosphere, Space Sci. Rev., 58, 193 (1991)
- Feldman, W.C., Asbridge, J.R., Bame, S.J. and Gosling, J.T.: High-speed solar wind flow parameters at 1 AU, J. Geophys. Res., 81, 5054 (1976)
- Fitzgerald, G.F.: Sunspots and magnetic storms, The Electrician, 30, 48 (1892)
- Forbush, S.E.: World-wide cosmic-ray variations 1937-1952, J. Geophys. Res., 59, 525 (1954)
- Gringauz, K.I., Bezrukikh, V.V., Ozerov, V.D. and Rybchinskiy, R.E.: Study of the interplanetary ionized gas, high energy electrons, and solar corpuscular radiation by means of three electrode traps for charged particles on the second Soviet cosmic rocket, Soviet Phys. "Doklady" (English Transl.), 5, 361 (1960)
- Hartle, R.E. and Sturrock, P.A.: Two-fluid model of the solar wind, Astrophys. J., 151, 1155 (1968)
- Helliwell, R.A. and Morgan, M.G.: Atmospheric whistlers, Proc. IRE, 47(2), 200 (1959)
- Hoffmeister, C.: Physikalische Untersuchungen an Kometen I. Die Beziehungen des primären Schweifstrahls zum Radiusvektor, Zeitsch. Astrophys., 22, 265 (1943)
- Hollweg, J.V.: Collisionless solar wind. 2. Variable electron temperature, J. Geophys. Res., 76, 7491 (1971)
- Hollweg, J.V.: Collisionless electron heat conduction in the solar wind, J. Geophys. Res., 81, 1649 (1976)
- Hundhausen, A.J.: Coronal Expansion and Solar Wind, Springer, New York (1972)
- Hung, R.J. and Barnes, A.: Dissipation of hydromagnetic waves with application to the outer solar corona. I. Collisionless protons and collisional electrons, Astrophys. J., 180, 253 (1973)

- Jockers, K.: Solar wind models based on exospheric theory, Astron. Astrophys., 6, 219 (1970)
- Kelvin, W.T.: Address to the Royal Society at their Anniversary Meeting, Nov. 30, 1892, Proc. R. Soc. (London), A52, 300 (1892)
- Leer, E. and Holzer, T.E.: Collisionless solar wind protons: a comparison of kinetic and hydrodynamic descriptions, J. Geophys. Res., 77, 4035 (1972)
- Marsch, E. and Richter, A.K.: On the equation of state and collision time for a multicomponent, anisotropic solar wind, Ann. Geophys., 5A(2), 71 (1987)
- Milne, E.A.: Emission of atoms from stars, Month. Not. R. Astron. Soc., 86, 459 (1926)
- Morrison, P.: Solar origin of cosmic-ray time variations, Phys. Rev., 101, 1397 (1956)
- Neugebauer, M.: The quasi-stationary and transient states of the solar wind, Science, 252, 404 (1991)
- Neugebauer, M. and Snyder, C.W.: Solar plasma experiment, Science, 138, 1095 (1962)
- Noble, L.M. and Scarf, F.L.: Conductive heating of the solar wind. I, Astrophys. J., 138, 1169 (1963)
- Parker, E.N.: Dynamics of the interplanetary gas and magnetic fields, Astrophys. J., 128, 664 (1958a)
- Parker, E.N.: Interaction of the solar wind with the geomagnetic field, Phys. Fluids, 1, 171 (1958b)
- Parker, E.N.: Interplanetary Dynamical Processes, Interscience, New York (1963)
- Parker, E.N.: Dynamical properties of stellar coronas and stellar winds. II. Integration of the heat-flow equation, Astrophys. J., 139, 93 (1964)
- Parker, E.N.: Dynamical theory of the solar wind, Space Sci. Rev., 4, 666 (1965)
- Pneuman, G.W.: Driving mechanisms for the solar wind, Space Sci. Rev., 43, 105 (1986)
- Sabine, E.: On periodical laws discoverable in the mean effects of the larger magnetic disturbances, Phil. Trans., 142, 103 (1852)
- Scarf, F.L. and Noble, L.M.: Conductive heating of the solar wind II. The inner corona, Astrophys. J., 141, 1479 (1965)
- Scudder, J.D. and Olbert, S.: The collapse of the local, Spitzer-Härm formulation and a global-local generalization for heat flow in an inhomogeneous, fully ionized plasma, Solar Wind Five, NASA Conf. Publ., 163 (1983)
- Spitzer, L. and Härm, R.: Transport phenomena in a completely ionized gas, Phys. Rev., 89, 977 (1953)
- Sturrock, P.A. and Hartle, R.E.: Two-fluid model of the solar wind, Phys. Rev. Lett., 16, 628 (1966)
- Toichi, T.: Thermal properties of the solar wind plasma, Solar Phys., 18, 150 (1971)
- Weber, E.J. and Davis, L.: The angular momentum of the solar wind, Astrophys. J., 148, 217 (1967)
- Weber, E.J. and Davis, L.: The effect of viscosity and anisotropy in the pressure on the azimuthal motion of the solar wind, J. Geophys. Res., 75, 2419 (1970)
- Whang, Y.C.: Conversion of magnetic-field energy into kinetic energy in the solar wind, Astrophys. J., 169, 369 (1971)
- Whang, Y.C. and Chien, T.H.: Expansion of the solar wind in high-speed streams, Astrophys. J., 221, 350 (1978)
- Wolff, C.L., Brandt, J.C. and Southwick, R.G.: A two-component model of the quiet solar wind with viscosity, magnetic field, and reduced heat conduction, Astrophys. J., 165, 181 (1971)