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16.Summary/Notes

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ASPECTS OF SOLAR WIND THEORIES

René A. Medrano-B.
Instituto de Pesquisas Espaciais - INPE
Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq
C.P. 515, 12200 São José dos Campos, S.P., Brazil

ABSTRACT

It is now more than two decades since the pioneering work of Parker in 1958, to explain the existence of a continuous corpuscular radiation in the interplanetary space. Yet, in spite of a considerable effort in this field, there is not a self-consistent theoretical model that is able to reproduce simultaneously all the solar wind parameters under quiet conditions. The discrepancy between theory and in situ satellite observations is even larger under disturbed conditions, especially during times of high-speed wind streams. A critical review of past and present theories is made in order to identify the main difficulties that should be surmounted by any modern theoretical model to achieve satisfactory results. It is found that the major difficulties are represented by a) insuficient knowledge about the damping of the MHD waves to heat the solar wind protons, b) the same problem with the electron heat conduction flux density for the collisionless interplanetary plasma. Also more experimental information about the (boundary) conditions of the low corona, which became more important after the coronal holes being identified as probable sources of the solar wind, should be obtained.

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René A. Medrano-B
Instituto de Pesquisas Espaciais - INPE
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C.P. 515, 12200 São José dos Campos, S.P., Brasil

1.0 - INTRODUCTION

Since the original work of Parker (1958), before the in situ interplanetary plasma measurements, a variety of theoretical models have been offered in order to describe the physics of what is now known as the solar wind. Although it has been more than two decades since Parker's pioneering work, there is not a self-consistent model that is able to predict all the plasma and field measurements under the most typical behavior of the solar wind. The reason that such models have not yet been developed is the topic of this review paper.

For the comprehensiveness of this work, some of the most known models, past and present will be reviewed, pointing out the difficulties in each case and progressing gradually in sophistication from the simplest to the present complex models.

First of all, it is necessary to remark that since the solar wind has been stablished to behave as a fluid in a macroscopic view, it seems natural to expect that it should be described by the conservation laws in absence of sources or losses, or more generally by the mass, momentum and energy equations. These equation can be written in several ways, depending primarely on the geometry of the boundaries and the physical effects that are thought to be important. However, and in order to make easier the comparisons among the different models, the equations just mentioned will be written in a general vector notation whenever possible. In fact, this has the advantage of avoiding unnecessary complications in the form of the expressions.

Biermann in 1951 (Parker, 1963) from the observations of comet ionic tails, suggested that the acceleration and ionization of the cometary molecules was due to interaction with an interplanetary background of ions flowing continuously and radially from the Sun, which he termed as corpuscular radiation. Parker (1958), apparently inspired by this idea, and almost no other information, solved the following set of conservation equations in stationary regime:

Mass equation: $\nabla \cdot (\rho \underset{\sim}{u}) = 0$ (1)

Momentum equation: $\nabla \cdot (\rho \underset{\sim}{u}\underset{\sim}{u} + p\underset{\approx}{I}) + \rho \, GM_s \dfrac{\underset{\sim}{x}}{|\underset{\sim}{x}|^3} = 0$ (2)

Energy equation: $\dfrac{p}{\rho^{\alpha}} = \text{const.}$ (3)

Where, ρ = mass density, $\underset{\sim}{u}$ = bulk flow velocity, p = thermal pressure, $\underset{\sim}{x}$ = radius vectors, $\underset{\approx}{I}$ = unit tensor, G = gravitational constant, M_s = mass of the Sun, and α = polytropic index. (Actually he used $\alpha = 1$ for an isothermal corona). Assuming spherical symmetry, with $T_e = T_p$, an $p = 2 \frac{\rho}{m} kT$, Parker solved equations (1) - (3) in a rather ingeneous manner to get a closed solution. Figure 1 shows the result of the integration of equations (1) - (3) under the following boundary conditions. a) Low expansion speeds deep in the corona and b) $\rho = 0$ as $|\underset{\sim}{x}| \to \infty$.

One of the remarkable results of Parker's theory (1958), was that he predicted the existence of an Archimedes spiral interplanetary magnetic field, due to the 25 days rotation of the Sun for a stationary observer (or 27 days for an observer on the Earth) and the existence of magnetic fields on the Sun's photosphere. The configuration of the interplanetary magnetic field, shown in Figure 2, was obtained by the simple argument that a solar magnetic field line, from a fixed point on the rotating Sun, is drawn out by the solar wind in an always radial direction and with speed u_s. Hence, with the Archimedes spiral equation

$$r - r_0 = \frac{u_s}{\omega \sin \theta} (\phi - \phi_0)$$

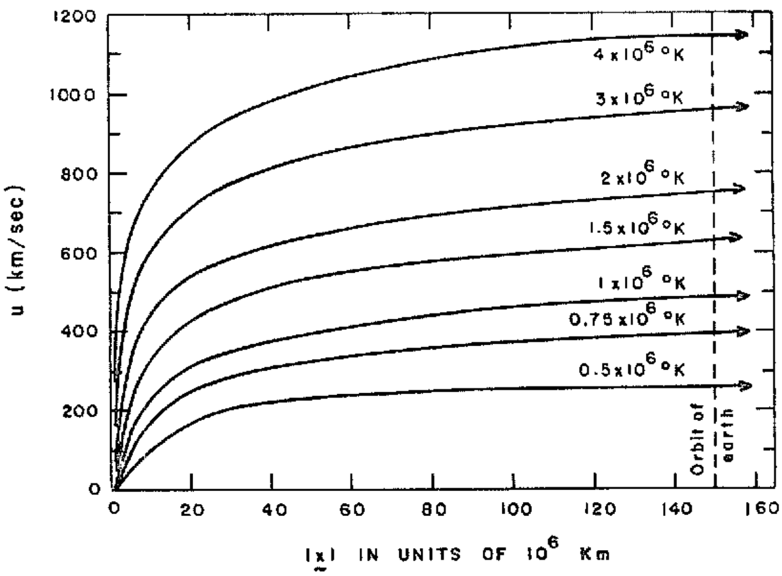


Fig. 1 - Expansion speed profiles for isothermal corona (different temperatures) as a function of helio centric distance (Parker, 1963).

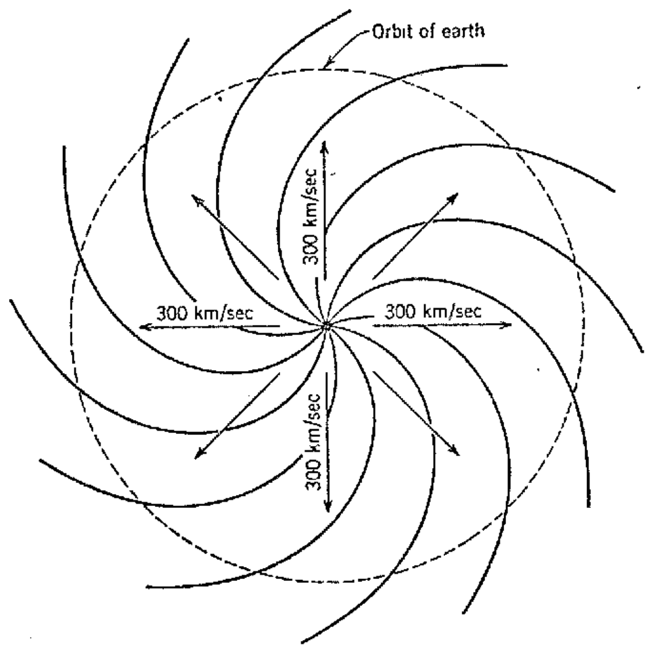


Fig. 2 - Interplanetary magnetic field configuration due to the rotation of the Sun, assuming a constant solar wind speed (Parker, 1963).

where r, θ and ϕ are the polar spherical coordinates, and ω the angular rotation velocity of the Sun, the differential equation of the field lines $d\underset{\sim}{x} \times \underset{\sim}{B} = 0$ and the Maxwell equation $\nabla \cdot \underset{\sim}{B} = 0$, Parker obtained the following components of the interplanetary magnetic field:

$$B_r\,(r, \theta, \phi) = B(r_0, \phi_0, \theta) \left(\frac{r_0}{r}\right)^2$$

$$B_\theta(r, \theta, \phi) = 0 \tag{4}$$

$$B_\phi\,(r, \theta, \phi) = -\,B(r_0, \phi_0, \theta)\,\frac{\omega r_0}{u_s}\,\frac{r_0}{r}\,\sin\theta$$

Where all zero indexes apply, for example, to the photosphere.

With the advent of the in situ measurements by space probes, it immediatly became evident that refined models were needed in order to explain the following average propective of the quiet solar wind(Montgomery et al., 1968, Hundhausen, et al., 1970, Ness et al., 1971, Hundhausen, 1972) and associated thermodynamic properties at 1 AU.

$< u_r >$ = Radial component of the bulk flow = 300 - 325 km/sec

$< u_\phi >$ = Azimuthal component of the bulk flow = 8 km/sec

$$< n > = \frac{1}{m_p} < \rho_p > = \frac{1}{m_e} < \rho_e > = 8.7 \ \frac{\text{particles}}{\text{cm}^3}$$

$< T_e >$ = Temperature of the electrons
= 1.5×10^5 K

$< T_p >$ = Temperature of the protons = 4×10^4 K

$< |\underset{\sim}{B}| >$ = 5 gammas

$$< \underset{\sim}{F} > = < n\underset{\sim}{u} > = 2.4 \times 10^8 \ \frac{\text{particles}}{\text{cm}^2\ \text{sec}}$$

$< \frac{1}{2} \rho u^3 >$ = Kinetic energy flux density = 0.22 $\frac{\text{ergs}}{\text{cm}^2 \text{ sec}}$

Electron heat conduction flux density = 0.007 $\frac{\text{ergs}}{\text{cm}^2 \text{ sec}}$

Proton heat conduction flux density ~ 0.00001 $\frac{\text{ergs}}{\text{cm}^2 \text{ sec}}$

2.0 - TWO FLUID MODELS

Parker's model is a one fluid-model, i.e. eventhough it considers a fluid (electrically neutral) of electrons and protons, the model implicity assumes that all the fluid properties of protons and electrons are alike.

An improvement of this model can be obtained by writting the full energy equation (in absence of sources) instead of the polytropic behavior assumed by Parker:

$$\nabla \cdot \left(\frac{1}{2} \rho u^2 \underset{\sim}{u} + \frac{\gamma}{\gamma - 1} p \underset{\sim}{u}\right) + \frac{GM_s \rho}{|\underset{\sim}{x}|^2} \underset{\sim}{u} = \nabla \cdot \underset{\sim}{q} \tag{5}$$

where γ is the heat capacity relation, $\underset{\sim}{q}$ is the heat conduction flux density, and all other quantities are the same as before. However, as a result of the observations, one is forced to think in terms of two-fluid equations since the temperature and heat conduction fluxes are different for both electrons and protons.

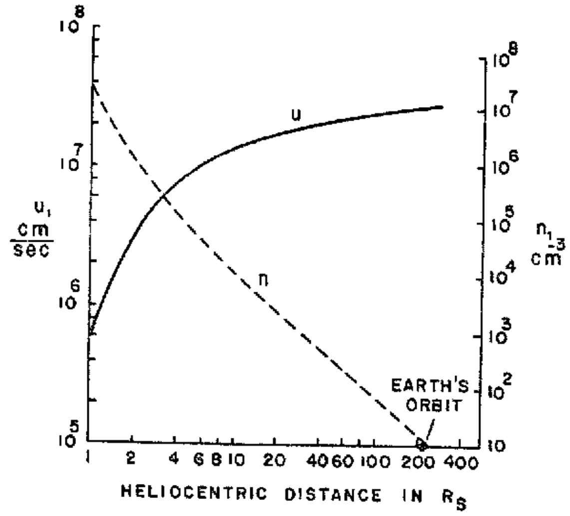
It is easily seen that the mass conservation equations, for both electrons and protons, is the same provided that each equation is written in terms of the number density n. On the other hand, the momentum conservation equation, in absence of sources, differs only in the thermal pressure term, since $p_e = nkT_e$ and $p_p = nkT_p$. Both equations can be combined into a single equation defining a new pressure $p = nk(T_e + T_p)$. Hence, equation (2) remains essentially the same.

The energy equation (5) should be written for each species primarily because the heat conduction term is different for electrons and protons.

$$\nabla \cdot \left(\frac{1}{2}\, nm_\alpha\, u^2 \underset{\sim}{u} + \frac{\gamma}{\gamma-1}\, p_\alpha \underset{\sim}{u}\right) + \frac{GM_s}{|\underset{\sim}{x}|^2}\, nm_\alpha = \nabla \cdot \underset{\sim}{q}_\alpha \qquad (6)$$

This energy equation corresponds to species α, where $\alpha = e, p$ (for electrons and protons) and $\underset{\sim}{q}_p = 0$.

Sturrock and Hartle (1966) have solved the set of equations (1), (2) and the two equations implied in (6), assuming spherical symmetry. (Actually, these authors considered a slightly modified expression for (6)). The expression for the heat conduction flux density they used, was the standard $\underset{\sim}{q}_\alpha = \kappa_\alpha \nabla T_\alpha$, where the heat conductivities $\kappa_{e,p}$ were assumed to correspond to a collision dominated fluid . Solution of the conservation equations with boundary conditions involving the specification of the particles number density and equal temperature at 1 R_s (solar radius), and the requirements that $T_e = T_p = 0$ as $|\underset{\sim}{x}| \to \infty$, are shown in Figures 3 and 4 where $n = 3 \times 10^7$ cm^{-3} and $T_e = T_p = 2 \times 10^6$ K at 1 R_s. Notice that at 1 AU: $n = 13$ cm^{-3}, $u = 270$ km/sec, $T_p = 2.8 \times 10^3$ K and $T_e = 4.6 \times 10^5$ K. Although these predicted values are encouraging,the following discrepancies should be noted. The predicted speed of the solar wind is lower than those observed under unperturbed conditions,however, the number density is higher than the average measured value; the proton temperature is one order of magnitude lower than the observations; the temperature of the electrons, predicted by this model, is more than three times the actual values. As a consequence of the last discrepancy, the electron heat conduction flux density becomes greater than those inferred from the observations. In fact, the heat conduction flux density from the theory becomes dominant at 1 AU, whereas the observations indicate that the dominant energy flux is due to the kinetic energy flux density. This discrepancy is very important because of its obvious physical consequences (the energy transport, as one canconclude from the model, is primarily due to heat conduction rather than hydrodynamic expansion).



. Fig. 3 - The flow velocity u and particle (either electrons or protons) number density n as a function of the radial distance from the Sun.

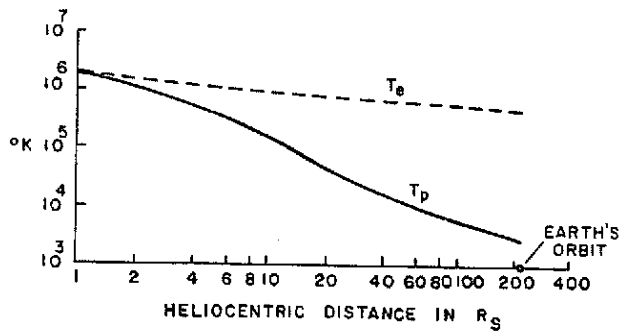


Fig. 4 - Electron temperature T_e and proton temperature T_p as a function of the radial distance from the Sun in solar radii R_s (Sturrock and Hartle, 1966).

It can still be argued that perhaps better results might be obtained by a more appropriate choice of the boundary conditions (e.g. a better choice for the temperature and density at 1 R_s). Hartle and Sturrock (1968) and Durney (1973) have attempted to obtain values for the solar wind parameters that agree with the observations by means of adjusting the numerical values of n and u al 1 R_s. Although it was possible to get satisfactory results for some of the parameters, not all simultaneous results were in agreement with the in situ measurements. In all cases it is found that the dominant energy flux at 1 AU is the electron heat conduction flux and the proton temperature is still low.

From what was said above, it becomes apparent that new theoretical features have to be taken into account in order to have solutions that predict a) higher proton temperatures and b) reduced heat conduction flux for the electrons, both for quiet solar wind conditions. It seems natural to look for sources that heat the protons and also to reconsider the validity of the expressions for the electron heat conduction flux which, in most of the models, are taken for a collision dominated plasma. Of course, from the kinetic theory point of view, it is known that the interplanetary plasma is a collisionless plasma at least from around 4 R_s out.

3.0 - NEW FEATURES IN THE SOLAR WIND THEORY

As in any magnetized plasma, magnetohydrodynamic (MHD) waves do exist in the solar wind and the damping of the fast mode waves has been considered as a mechanism of heating the collisionless plasma (Barnes, 1966, 1968, 1969; Holloweg, 1973a, 1973b, 1975, 1978a). If the angle between $\underset{\sim}{k}$ and $\underset{\sim}{B}_0$ (where $\underset{\sim}{k}$ is the wave vector and $\underset{\sim}{B}_0$ the ambient magnetic field) is not near $\pi/2$, then primarily the protons are in resonance (Landau damping) with the wave and therefore heated. If, in the other hand, these two vector quantities are nearly orthogonal, then the electrons are heated (Barnes, 1968). In the region inside 0.5 AU, the angle between $\underset{\sim}{k}$ and $\underset{\sim}{B}_0$ is most probably less than $\pi/2$ and, therefore, heating of protons should be expected. This also means that at distance more than 0.5 AU, the flux of fast mode MHD waves must be low.

The slow mode MHD waves are expected to damp so rapidly that they might not survive far from the Sun (Barnes, 1969) and, therefore, can heat only the lower corona.

The Alfvēn MHD mode does not damp in small-amplitude plasma theory and this is why it is observed at 1 AU. However, the large-amplitude waves are subjected to a nonlinear damping because of the curvature of the interplanetary magnetic field that causes "decay" into slow and fast mode waves, respectively, which are then Landau damped. This means that the Alfvēn waves are one of the most probable candidates to provide a continuous heating of protons. The energy lost by the wave $\delta|\underset{\sim}{B}|^2/8\pi$, via nonlinear damping, can then be introduced into the conservation equations as a source term. However, the task of relating the Landau-damping of the waves and the process of heating is a difficult problem. This problem was noted by Hollweg (1978a, b) while investigating the effect of a simulated damping of the Alfvēn waves. Hollweg's work will be mentioned again later.

Another aspect that needs much attention from the theorists is the proper way of handling the electron heat conduction flux density. As was pointed out at the end of last section, the contribution of heat conduction plays a significant part in the total energy density flux in contradiction to the experimental observations. The main problem of most of the solar wind models seems to lie in the expression for the electron heat conduction flux density $\underset{\sim}{q}_e$ since all assume that

$$\underset{\sim}{q}_e = - \kappa \nabla T_e \tag{7}$$

where κ is the thermal conductivity which is commonly taken from collision dominated treatments such as that given by the standard formula of Spitzer and Härm(1953). Equation (7) might be all right for heliocentric distances close to the base of the corona, but certainly cannot apply beyond $4R_s$, where the interplanetary plasma becomes collisionless. Since in terms of kinetic theory it does not make sense to talk about heat conduction without collisions, it can be realized that the derivation of an expression for the heat conduction flux density is not an easy task.

Perkins (1973) proposed that the electron thermal conductivity κ in the collisionless (except Coulumb collisions) solar wind can be estimated by

$$\kappa = (\Delta r)^2 \, \nu_e \, n_e$$

where ν_e is the Coulumb collision frequency, n_e the electron number density and Δr a characteristic distance where the electrons are considered to be trapped by a magnetic mirror near the Sun and by an electrostatic potential hill far from it. Hollweg (1974), considering the same picture idealized by Perkins, but under the argument that a measure of the skewness of the electron distribution function should be associated to the heat conduction flux, and assuming that the solar wind speed is a measure of such skewness, produced an expression which applies to a collisionless situation.

$$\underset{\sim}{q}_e = \frac{3}{2} n_e \, k \, T_e \, (\underset{\sim}{u} - \underset{\sim}{\omega} \times \underset{\sim}{x})\alpha \tag{8}$$

where $\underset{\sim}{\omega}$ is the angular rotation velocity of the Sun, α is a parameter that depends on the exact shape of the distribution function, and the other quantities are the same as those defined above.

Assuming the correctness of expression (8), for the heat conduction flux density in the collisionless solar wind, it is apparent that a further difficulty will arise in theoretical models, especially in the transition region from collision dominated to collisionless solar wind. Actually, this is one of the unsolved problems faced by theoreticians.

Still there is another major difficulty that became of serious concern after the observations by the Skylab experiments (Zirker, 1977) which, in combination with satellite and ground based observations (Suess, 1979; Barnes, 1979), provided the basis for the identification of coronal holes as sources for the high speed solar wind streams. The Skylab observations also indicate that the coronal holes may even be continuous sources for the solar wind plasma. Consideration of the coronal holes in solar wind theory is important because the geometrical configuration of the coronal holes can change considerably the boundary conditions at the base of the corona, where most models assume spherical symmetry.

Coronal holes are regions of the corona, which appear dark not only in eclipse photographs but also in the images that are obtained from X-ray and white light coronagraphs. Figure 5 shows a superposition of the corona during the eclipse of November 1966, the white light coronagraph and the result of the magnetic field configuration calculations (Newkirk et al., 1970). In this picture, the dark regions in both the north and south poles should be noted (top and botton of the solar disk, respectively), which correspond to two large coronal holes. The association of open magnetic fieldlines with dark regions should be easy to realize since the plasma would flow out leaving these regions with relatively low particle populations. Whereas those bright regions can be interpreted as trapping regions and hence closed field lines.

Comparison of Skylab solar data and interplanetary data from the same period shows a very strong correlation between large, near-equatorial coronal holes and high-speed wind solar streams (Hundhausen, 1977). Figure 6 shows a comparison of the solar wind speed (upper figure)

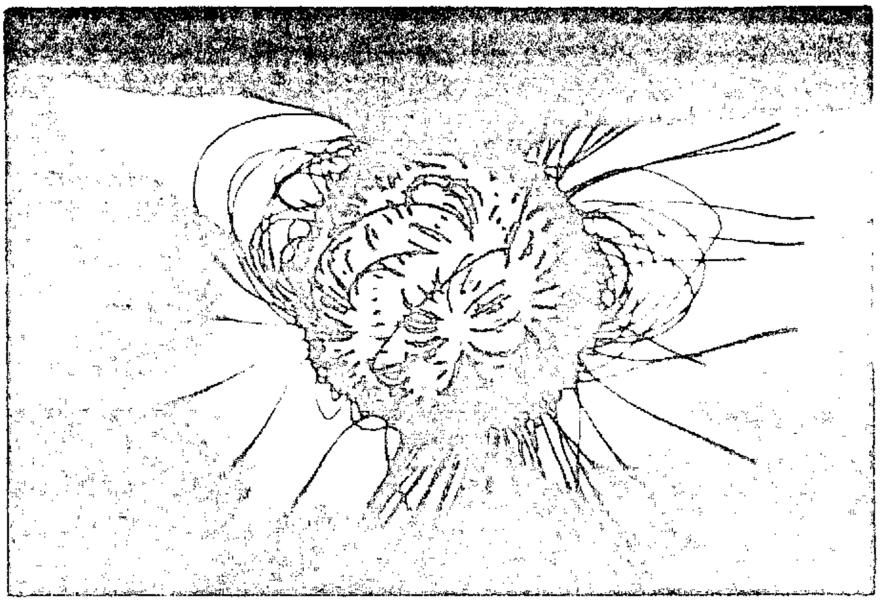


Fig. 5 - Superposition of calculated coronal magnetic fields lines with the Nov. 22, 1966 eclipse photograph of the solar corona (Newkirk et al., 1970).

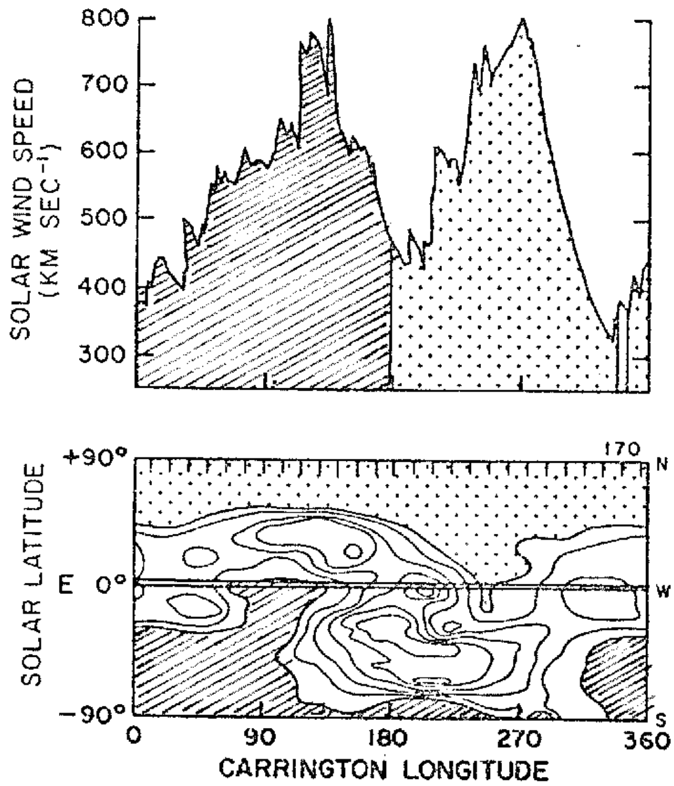


Fig. 6 - Solar wind speed (above), plotted as a function of solar longitude, is compared with K Coronameter data (below). The shaded regions and those filled with positive signs correspond to negative and positive magnetic polarity, respectively (Hundhausen, 1977).

with contours of constant K coronal emission intensity on the Sun (lower figure). The solar wind speed is plotted as a function of solar longitude and the region filled with plus signs represents the magnetic polarity of the streams. The shaded regions represents the opposit polarity. On the lower figure, the plus and shaded regions also represent the magnetic polarity of the field, in the polar coronal holes. From this Figure, it becomes apparent that the photospheric magnetic fields in coronal holes have the same polarity as the streams. More recently Schwenn et al. (1978) and Burlaga (1979) have confirmed these results, using data from several spacecrafts.

As a consequence of these relevant results, it seems fairly clear that the interplanetary field lines are extension of the open field lines from coronal holes. This might imply that the solar wind originates from a small part of the solar surface, since coronal holes are estimated to occupy $\leq$ 20% of the solar surface (Levine et al., 1977a, b). If this is true, from mass and energy conservation arguments, one can conclude that high mass and energy fluxes in the low corona must be expected. This, of course, represents an obvious difficulty for the solar wind models because, not only the boundary conditions have to be revised, but also the geometry of the "boundary" as well.

4.0 - MODELS THAT INCLUDE THE NEW FEATURES

From what was said in the previous section, it should be expected that any theoretical model, which includes the "new" physics and which predicts the observed quiet-time solar wind parameters, should also predict the high-speed solar wind stream conditions, since it appears that the plasma, either quiet or disturbed, originates as a result of nearly the same dynamics in the low solar corona. This model simply does not exists at the present time.

Hollweg (1978b) has included the contributions of Alfvēn waves in the set of equation (1), (2) and (6) and also the expression for the electron heat conduction flux density for a collisionless solar wind that he derived (Hollweg, 1974). He also assumed a non-r^2 divergence of the magnetic field lines in the corona. Figures 7 and 8 show solutions for the specified conditions that pressumably represent the conditions at 1 R_S during high-speed streams. The anomalous behavior of a) the electron temperature T_e (a kink at about 10 R_S) and especially of b) the proton temperature T_p(abrupt increase of T_p at 20 R_S) is only a consequence of the use of two formulae for the electron heat conductions (one collision-dominated and another collisionless expressions) which is responsible for the kink in the T_e profile, and an artificially introduced constant damping of the Alfvēn waves starting at 20 R_S which causes the abrupt increase in T_p. The purpose of Hollweg's work was to demonstrate the influence of introducing the new features that have to be considered in modern models and, therefore, the results shown in Figures 7 and 8 should not be interpreted in physical terms. Anyhow, Hollweg's results demonstrate the desired decrease in T_e and increase in T_p.

Joselyn and Holzer (1978) have worked out a three-fluid coronal expansion with the purpose of investigating the effect of rapidly diverging flow tubes. Although they did not include the electron heat conduction term in their equations, and, therefore, did not obtain useful results at 1 AU, these researchers have found that the presence of a rapidly diverging flow geometries in the corona causes larger ion number flux densities near the base of the corona, than would be inferred for a spherically symmetric flow geometry.

5.0 - CONCLUDING REMARKS

In summary, there are still some solar wind phenomena that are known to exist on a permanent basis but which need an extensive study before being used in theoretical models in the solar wind. An expression for the electron heat conduction flux density is yet to be developed, such that its behavior close to the Sun is that of a collision dominant fluid and have a smooth transition to the region where the interplanetary plasma is known to be collisionless. The energy deposition by the MHD waves, heating and accelerating the protons, is known only an a qualitative basis

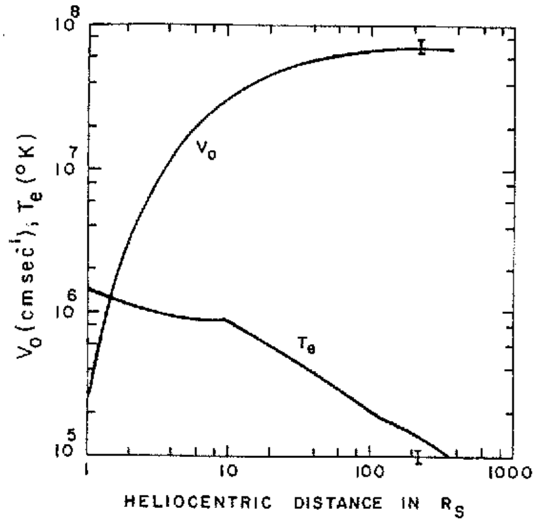


Fig. 7 - Solar wind speed v and electron temperature T_e as functions of heliocentric distance in solar radii for conditions at the Sun's surface: $n = 6 \times 10^7$ cm^{-3}, $T_e = T_p = 1.5 \times 10^6$K, and Alfvēn wave energy flux density $P_A = 4.8 \times 10^5$ ergs cm^{-2}sec^{-1} (Hollweg, 1978b).

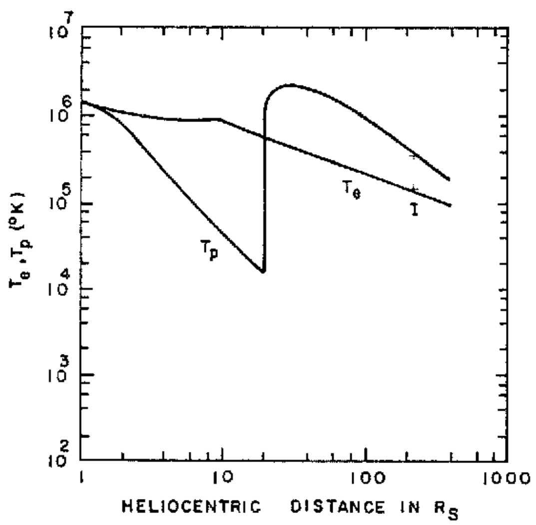


Fig. 8 - Proton and electron temperatures as functions of the heliocentric distance in solar radii for the conditions of Fig. 7. (Hollweg, 1978b).

and it is the topic that needs most attention. Finally, the boundary conditions at the base of the corona, including the geometry of the boundary, must be investigated experimentally.

It should also be mentioned that all models are tested to match the experimental observations on (or near to) the ecliptic plane, primarily because little informations is known at higher heliolatitudes. (In fact, some of the models use the observations at 1 AU as boundary conditions). This should not be taken as a limitation but should be kept in mind at least until in situ measurements are made at polar heliolatitudes. In this respect, Smith et al. (1978) reported new important information at 16^0 heliolatitude from data of Pioneer 11. They found that the sector boundaries that are always observed in number of 2, 4 or sometimes 6 in one solar rotation, were not observed in these regions. This finding led the authors to suggest that the interplanetary space is divided into two hemispheres with opposite magnetic polarities (like a dipole structure) however with a current sheet on a plane that might be tilted with respect to the solar equator. Figure 9 shows the three dimensional configuration of the current sheet. An observer on the ecliptic plane would alternatively see opposite polarities according to his position whether above (positive) or below (negative) the current sheet. This idea has been suggested in the past (Schulz, 1973; Svalgaard and Wilcox, 1976) while trying to explain the sector structure observations. Indeed, in this picture, the current sheet might be the well known sector boundaries.

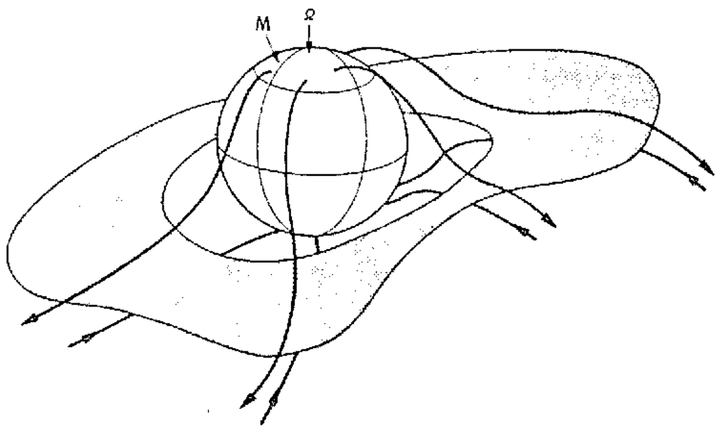


Fig. 9 - Model of the interplanetary current sheet responsible for the sector structure. M and Ω are the normal to the current sheet and rotation axis of the Sun, respectively (Smith et al., 1978).

Based on the recent experimental observations that have been mentioned above, one can surmise that the geometry of the coronal hole flow tubes, that generate the continuous emission of the interplanetary plasma, is that shown in Figure 10. This Figure illustrates the configuration of the magnetic fields low in the corona, showing the flow tubes (coronal holes) that might be responsible for the low-speed (fast diverging tubes) and high-speed (less diverging tubes) solar wind particles.

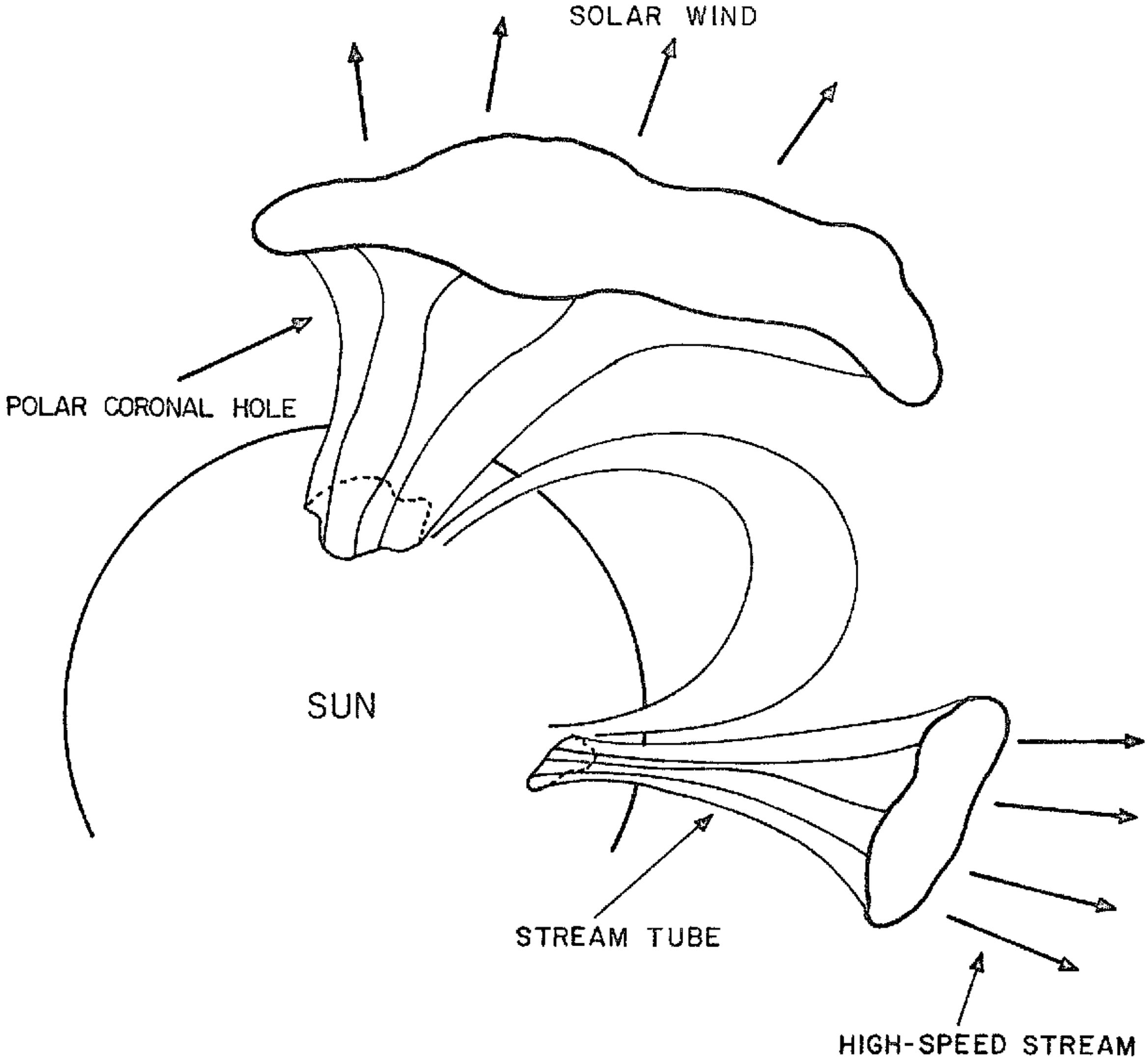


Fig. 10 - Artistic conception of what the geometry of the (coronal holes) magnetic flow tubes low in the corona might be.

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