THE SOLAR WIND

W. I. AXFORD

Max Planck Institut für Aeronomie, Katlenburg-Lindau, F.R.G.

Abstract. The current status of our understanding of the nature and origin of the solar wind is briefly reviewed, with emphasis being placed on the need for wave-particle interactions to account for the main energy source as well as details of the particle distribution functions. There has been considerable progress in the theoretical treatment of various aspects of the physics of the solar wind but a complete understanding is not yet in sight. Arguments concerning the ultimate fate of the solar wind are reviewed, in particular those concerning the distance to the shock wave which marks the termination of supersonic flow. This is of particular significance in view of recent observations suggesting that the termination might occur at about 50 AU from the Sun.

1. Introduction

The solar wind as an inference from cometary observations has been known for about 35 years, as a theoretical development, due to Parker, for almost 30 years and as a subject of direct observations by spacecraft for about 25 years. Both in terms of theoretical advances and the wealth of new information made available from experiments carried by dozens of spacecraft in the last two decades, the study of the solar wind has become one of the most elegant and intellectually satisfying branches of space plasma physics. The general concept of such winds has been extended to include not only stellar winds in general, but winds from comets and the outer envelopes of planets at one extreme, to winds from galactic clusters, galaxies and clusters of galaxies at the other. Consequently, there is a convincing case to be made for studying the solar wind in as much detail as possible in all its aspects since it is rare that we have a chance to make detailed observations of a phenomenon of such general astrophysical significance.

However, before getting too carried away with enthusiasm for the solar wind as a phenomenon, it is worth remembering, that, as far as the Sun itself is concerned, the black-body radiation of the photosphere is far more important than the solar wind in terms of mass loss, energy flux and momentum flux. The present solar wind is by comparison only important for the angular momentum loss of the Sun as a whole (see Table I). Furthermore, despite strenuous efforts in recent years to prove the contrary,

TABLE I

Relative importance of solar wind and radiation

	Solar wind	Radiation
Mass loss rate	10^{12} g s^{-1}	4×10^{12} g s^{-1}
Total mass lost	$5 \times 10^{-5} M_*$	$2 \times 10^{-4} M_*$
Energy flux (1 AU)	0.16 erg cm^{-2} s^{-1}	1.4×10^6 erg cm^{-2} s^{-1}
Momentum flux (1AU)	8×10^{-9} g cm^{-1} s^{-1}	5×10^{-5} g cm^{-1} s^{-1}
Despin time	10^{10} yr	10^{12} yr

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the solar wind appears to affect the Earth only in the upper atmosphere above about 100 km altitude and in the polar regions, although there are some fairly esoteric arguments that it may have a dominant role in determining the atmospheric abundances of some minor constituents such as ^{3}He.

On the other hand, in the distant past, when the solar system was being formed, the situation may well have been different. The solar wind at the time, is likely to have been sufficiently strong to have carried away most of the angular momentum of the primordial Sun, to have dissipated the disc-shaped nebula which must have formed its extended outer atmosphere and in so doing may well have determined the different characteristics of the inner and outer planets.

2. Why Does the Solar Wind Blow?

During the mid 1950s it was evident from observations of the behaviour of the plasma tails of comets, the almost continual presence of aurorae and associated phenomena in the Earth's polar regions and the apparent absence of a general, extended hydrostatic solar corona, that the solar wind must exist. Parker (1963, 1969; and earlier papers cited therein) pointed out that a continually expanding wind should be a natural consequence of the existence of a hot corona and furthermore that, since the pressure of the interstellar medium is so small, a hydrostatic corona could not possibly be sustained as a consequence of thermal conduction. In fact the latter argument must be altered slightly if one takes into account the existence of a solar magnetic field, but even then some sort of solar wind would have to flow from the Sun's magnetic polar regions.

Chamberlain (1961, 1965) attacked Parker's views in a series of papers which claimed that, with heat conduction taken into account, the solar wind might be nothing more than an innocuous subsonic solar 'breeze'. These arguments soon lost any force they may have had as a result of *in situ* observations by Soviet and US spacecraft which confirmed the existence of the solar wind, as inferred from cometary observations, and in the form of a supersonic radial outflow with an imbedded spiral magnetic field as predicted by Parker. For reviews of these earlier observations see Axford (1969) and Hundhausen (1968).

Now that we know so much about the solar wind one can return to these early arguments and examine them again. In particular it should be noted that solar wind protons observed at 1 AU typically have kinetic energies of the order of 10^3 eV and more. Since the thermal energy available to such protons and their associated electrons when they form part of the lower corona is only about 430 eV and the gravitational binding energy is about 2000 eV it is immediately apparent that the solar wind must be rather more than simply the adiabatic expansion of a hot corona (see Table II). Evidently some means of transferring energy non-adiabatically to the outer corona, such as heat conduction, must play an important role. However, even taking the effects of heat conduction into account in the most generous way one finds that a solar wind would exist (despite Chamberlain's arguments), but its characteristics would not match those

TABLE II

Energy comparison

Energy	Base of corona	Slow stream	Fast stream
Gravitational ($-GMm/r$)	-2000 eV	–	–
Thermal ($5k(T_p + T_e)/2$)	430 eV	30 eV	60 eV
Kinetic ($mV^2/2$)	–	1000 eV	4000 eV
Total[a]	-1570 eV	$+1030$ eV[b]	$+4060$ eV[b]

[a] The average solar wind energy flux is $\sim 8 \times 10^5$ erg cm^{-2} s^{-1} which is about the same as the transition zone UV radiation flux.

[b] The plasma must be given 2600–5630 eV/e–p pair in addition to the energy it has at the base of the hot corona ($\sim 1.5 \times 10^6$ K).

of the observed solar wind, namely in that it would be slow, the ions too cool and the electrons too hot (Hartle and Sturrock, 1968).

In order to account for the basic features of the solar wind, it is necessary to assume as a minimum that there is an energy source which is distributed throughout the corona and solar wind close to the Sun (e.g., Holzer and Axford, 1970) and that the effects of electron heat conduction are suppressed substantially below those predicted by the Spitzer–Harm model for the conductivity (e.g., Forslund, 1970). In these circumstances it is inappropriate to treat the heating of the corona itself as a separate matter; presumably, the energy sources for the heating of the corona, for the radiation from the chromosphere-corona transition region and for the solar wind are ultimately the same and the whole system must be regarded as a single phenomenon. It is in fact interesting to note that for equal areas at the base of the corona, the energy flux associated with high-speed solar wind streams is comparable to the energy flux of the transition region radiation in regions with generally closed solar magnetic field lines where the corona is effectively hydrostatic and the solar wind at most intermittent. This energy flux is of the order of 10^6 ergs cm^{-2} s^{-1}.

The source of the energy required as far as the corona and solar wind are concerned, seems likely to be associated with hydromagnetic waves of one sort or another which are damped as they propagate away from the Sun (e.g., Hollweg, 1983). Whether the wave amplitudes are so large that they should be considered as shocks or they are no more than midly nonlinear is unclear. However, some remnant of the heating process appears to persist out to very large distances from the Sun, perhaps even to the Earth's orbit. The source of these waves is not known though there are several possibilities, each with an adequate reservoir of energy, notably the relatively large-scale motions associated with the solar supergranulation and, at the other extreme, microflare and other small-scale features such as spicules which may be associated with magnetic reconnection and localized heating.

In passing it should be noted that although the solar wind, particularly in high-speed streams, is almost collisionless in the sense that the mean-free path near the Earth's orbit is typically of the order of an astronomical unit or larger, a purely collisionless 'exopheric' model for the solar wind fails to produce its observed characteristics. For example, if it is assumed that the distribution function is collision-dominated and Maxwellian in the moving frame out to a few solar radii and beyond that totally collisionless and free from any wave forces, it is found that the predicted solar wind speed is far too low and the ratio of parallel to perpendicular proton temperatures greatly exceeds unity in contradiction to the observations. Furthermore, the behaviour of heavier species, especially those with large mass-to-charge ratios, predicted by such a model again cannot be made to agree with observations which show that, in high speed streams where the model is most likely to be appropriate, the relative abundances of various species are close to the expected solar abundances. In the case of low speed streams, Coulomb collisions between ions are very important in maintaining distribution functions which are almost isotropic in the solar wind frame and in forcing different species to move together and have comparable temperatures. For these reasons, it is necessary to adopt a multi-fluid approach to solar wind theory while recognising that collisionless processes are important in determining wave damping and in the transfer of energy and momentum from waves to particles (e.g., Marsch *et al.*, 1982).

It is evident from observations of high speed streams that a relatively large distances, the behaviour of the solar wind is determined to a large extent by wave-particle interactions involving waves which originate near the Sun, (e.g., Hollweg, 1974; Feldman, 1979; Barnes, 1979; Schwartz, 1980; Marsch, 1985):

(1) The perpendicular temperature is usually larger than the parallel temperature which is the opposite to what would be expected in the absence of preferential absorption of wave energy into perpendicular motion in the solar wind frame;

(2) all ionic species tend to have the same temperature per unit mass; and

(3) heavier species tend to move slightly faster than the protons which is very difficult to explain in terms of a collison-dominated or totally exospheric model.

It seems possible to understand these effects only on the basis of wave-particle interactions, with cyclotron resonance effects being important in some way since this permits variations in the behaviour of species with differing charge/mass ratios as a result of resonance with different parts of the wave spectrum.

In slow streams, which are evidently associated with magnetic sector boundaries (see Neugebauer, 1983), the above factors are absent, as to a large extent is magnetohydrodynamic turbulence (Denskat and Neubauer, 1983). The minor species have highly varying relative abundances, although their charge states indicate an origin in a reasonably hot corona (Bame, 1983). It seems likely that this type of solar wind has its origin in regions of the corona which are magnetically open only transiently so that they do not represent an equilibium state of the solar wind (Axford, 1977).

3. Two-Fluid Models of the Solar Wind

As a first approach to modelling the solar wind, taking into account the various physical processes alluded to above, one can consider the case of sphericially symmetric flow of a proton-electron plasma with an extremely weak spiral magnetic field. A minimum set of equations describing such a situation would be (see Holzer and Axford, 1970):

$$NUr^2 = F = \text{constant}\,, \tag{1}$$

$$NmU\frac{\mathrm{d}U}{\mathrm{d}r} + \frac{\mathrm{d}}{\mathrm{d}r}[Nk(T_p^{\parallel} + T_e)] + \frac{2}{r}Nk(T_p^{\parallel} - T_p^{\perp}) + \frac{GM_*}{r^2} = H\,, \tag{2}$$

$$\frac{\mathrm{d}T_p^{\parallel}}{\mathrm{d}r} = \frac{T_p^{\parallel}}{N^2}B^2\frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{N^2}{B^2}\right) + \frac{2\nu_{pp}}{U}(T_p^{\perp} - T_p^{\parallel}) + \frac{2Q_p^{\parallel}r^2}{kF}\,, \tag{3}$$

$$\frac{\mathrm{d}T_p^{\perp}}{\mathrm{d}r} = \frac{T_p^{\perp}}{B}\frac{\mathrm{d}B}{\mathrm{d}r} + \frac{\nu_{pp}}{U}(T_p^{\parallel} - T_p^{\perp}) + \frac{2Q_p^{\perp}r^2}{kF}\,, \tag{4}$$

$$\frac{\mathrm{d}T_e}{\mathrm{d}r} = \frac{2}{3}\frac{T_e}{N}\frac{\mathrm{d}N}{\mathrm{d}r} + \frac{\nu_{pe}}{U}(T_p - T_e) + \frac{2}{3kF}\frac{\mathrm{d}}{\mathrm{d}r}\left[Kr^2\cos^2\psi\frac{\mathrm{d}T_e}{\mathrm{d}r}\right] + \frac{2Q_er^2}{kF}\,. \tag{5}$$

Here U is the solar wind speed, N the number density, G the gravitational constant, T the temperature, k Bolzmann's constant, K the electron thermal conductivity, ν the collision frequency, B the magnetic field strength, Q a heat source, H a momentum source, and ψ the angle between the magnetic field lines and the radial direction. Subscripts p, e refer to protons and electrons respectively and the superscripts $\parallel$ and $\perp$ refer to the parallel and perpendicular directions relative to the magnetic field.

Hartle and Sturrock (1968) have solved this set of equations with the simplifying assumption that the temperature is known in the corona and that the heat and momentum sources are otherwise absent, that the magnetic field is radial and that the proton temperature is isotropic. Even modifying their results to allow for a spiral magnetic field and supressing the value of the heat conductivity to below the Spitzer-Harm value, it is not possible to obtain a realistic model of the solar wind with reasonable coronal temperatures. It is evidently necessary that the heat be injected in a distributed manner rather than in a narrow region at the base of the corona, and that the proton temperature at least should be allowed to be anisotropic. Leer and Axford (1972) have explored models of this type, assuming $H = 0$, and find that it is possible to achieve more satisfactory results with a suitable assumption for the heat source, but that it is necessary to have $Q_p^{\perp} \gg Q_p^{\parallel}$ in order to keep $T_p^{\perp} > T_p^{\parallel}$ as is observed. With such models it is, in principle, possible to permit a realistic treatment of the chromosphere-corona transition region by assuming a suitable chromospheric temperature and cooling function. However the procedure is unfortunately rather arbitrary in the sense that the energy and momentum transfer required from the presumed field of magnetohydrodynamic waves is postulated on a completely ad hoc basis.

The relevant equations allowing for the presence of Alfvén waves have been developed by Belcher (1971). As a consequence of the nearly incompressible character of these waves a convergent iterative sheme exists for solving the coupled 'background' and 'propagation' equations. Assuming that the waves do not damp but propagate according to WKB theory, one finds that energy and momentum are transferred from the waves to the fluid without dissipation so that

$$H = -\frac{r^2}{F}\frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{b^2}{8\pi}\right), \qquad Q = 0\,, \tag{6}$$

where b is the wave amplitude. A possible resonant contribution to H has been neglected. These equations have been solved under certain simplifying assumptions, notably that the electrons and protons behave isothermally (Hollweg, 1978). However such a model is not entirely satisfactory since the relative wave amplitude becomes large in the absence of dissipation, which is not observed, at least if near-Sun amplitudes sufficiently large to drive the solar wind are required. In fact, some form of non-linear damping may limit the wave amplitude such that $b \lesssim B$. In order to satisfactorily deal with this situation it would be necessary to solve the wave propagation equations allowing for dissipation (possibly nonlinear) in which case H and Q are both nonzero. Consequently the waves may drive the wind directly through their radiation pressure gradient and also indirectly by heating the plasma so that it behaves nonadiabatically.

The observation that $T_p^{\perp} > T_p^{\parallel}$ in high-speed streams suggests that cyclotron damping is important at some stage of the wave dissipation process. This complicates matters further, however, as the propagation of Alfvén waves is affected by pressure anisotropies and instabilities can occur if the anisotropy becomes too large in either sense. Perhaps the simplest first approach to dealing with these complexities would be to assume that $b \approx B$ everywhere that H is determined by the equivalent wave pressure gradient as before, that the waves remain Alfvénic and that the lost wave energy appears in $Q_p^{\perp}$ only (e.g., Isenberg and Hollweg, 1982).

4. The Behaviour of Minor Species

It is striking that the minor constituents of the solar wind plasma in high-speed streams have fairly constant relative abundances (similar to those expected from the photosphere), equivalent temperatures which are roughly proportional to ion mass and a tendency to move faster than the proton component by an amount approximately of the order of the Alvén speed. In low-speed streams the effects of Coulomb collisions are apparent since the temperatures and speeds of all ionic species tends to become equal, but the relative abundances are quite variable.

One cannot account for any of the features of high-speed streams if Coulomb collisions play a significant role other than in the lower corona. Instead it is necessary once again to invoke wave-particle interactions in a manner consistent with that described above for a two-fluid model. Provided the waves concerned are Alfvén or ion cyclotron waves, which are incompressible to first order, a quasi-linear approach similar to that outlined above for the two fluid model permits some progress to be made provided the concentrations of minor species are small and their presence does not affect the behaviour of the proton and electron components.

The relevant equations of motion of minor species with atomic mass Am and charge

Ze, to be combined with (1)–(6) for example are:

$$nAmur^2 = F_i = \text{constant}\,, \tag{7}$$

$$u\,\frac{\mathrm{d}u}{\mathrm{d}r} - \frac{w^2}{r} = \frac{\Omega u}{U}\,\frac{\mathrm{d}}{\mathrm{d}r}\,(wr) + v_{ip}(U-u)\,(1 + (\Omega r/U)^2) - \frac{Z}{Amn}\,\frac{\mathrm{d}b_e}{\mathrm{d}r} - \\ -\frac{1}{nm}\,\frac{\mathrm{d}}{\mathrm{d}r}\,(nkT_i) - \frac{GM_*}{r^2} + H_i + H_i(\mathrm{res})\,, \tag{8}$$

where

$$w = (U-u)\,\Omega r/U\,, \tag{9}$$

and

$$H_i = \frac{\mathrm{d}}{\mathrm{d}r}\left[\frac{b^2}{2B_r^2}\left((U+V_{Ar})^2 - u^2\right)\right], \qquad Q_i = 0\,. \tag{10}$$

Thus

$$u\,\frac{\mathrm{d}u}{\mathrm{d}r} - U\,\frac{\mathrm{d}U}{\mathrm{d}r} = \frac{1}{2}\,\frac{\mathrm{d}}{\mathrm{d}r}\left[(u^2-u^2)\left(\frac{b^2}{B_r^2} + \left(\frac{\Omega r}{U}\right)^2\right)\right] + \\ + v_{ip}(U-u)\,(1+(\Omega r/U)^2) + H_i(\mathrm{res}) - H(\mathrm{res}) - \\ -\left[\frac{1}{Amn}\,\frac{\mathrm{d}}{\mathrm{d}r}\,(nkT_i) - \frac{1}{Nm}\,\frac{\mathrm{d}}{\mathrm{d}r}\,(Nk(T_p+T_e))\right] - \frac{Z}{Amn}\,\frac{\mathrm{d}}{\mathrm{d}r}\,(NkT_e)\,. \tag{11}$$

Here n, $m_i = Am$, $u = (u, v, w)$, T_i are the number density, atomic mass, flow velocity, and temperature of the minor species, respectively, Ω is the angular frequency of solar rotation and H_i (res) is the resonant component of momentum transfer from waves.

On examining these equations one notes first from (10) that the non-resonant wave acceleration of all minor species vanishes if $u = U + V_{Ar}$, as might be expected since the waves are effectively static structures in this frame of reference. However, if one considers the difference between the minor ion and proton accelerations (Equation (11)) it is evident in the absence of pressure gradients and resonance effects, the solution $u = U$, $w = 0$ is an acceptable one and the pressure gradients alone would tend to make $u < U$ unless T_i is quite large. There is evidently not enough physics in this treatment to suggest why the minor species in high-speed streams should have $u \approx U + V_{Ar}$ and $T_i \approx AT_p$. As with the two-fluid model, a WKB account of the wave propagation is unsatisfactory since it permits the waves to become strongly non-linear ($b > B$) in contradiction to the observations. If wave dissipation is included in the analysis it is no longer obvious that the non-resonant and resonant contributions to H, H_i and to Q, Q_i should not change from the values given in (6) and (10).

Since most observed Alfvén waves in high-speed streams are such that $b \approx B$ it would appear that their amplitudes may be controlled by nonlinear damping processes, regardless of the presence of minor species. However at any given distance from the Sun, the wave spectrum affects, and is affected by, various species according to their charge/mass ratios and their concentrations, with protons perhaps being least prone to resonance effects. The observation that $u \approx U + V_{Ar}$ may be the result of resonant acceleration/heating of minor species being otherwise dominant in equations (8) and (11), which should then be approximated by $H_i(res) = 0$ which would imply the required result. As a corollary it should be expected that the most important component of the momentum transfer is associated with the Lorentz force of the waves rather than the 'centrifugal' force (McKenzie *et al.*, 1979, Appendix D). However, the argument does not suggest an explanation for the observation that $T_i \approx AT_p$ in high-speed streams and indeed any approach along the lines outlined must fail since only incompressible (transverse) waves are permitted with the temperatures playing no clear role. Models with compressible modes are required and it has been demonstrated that an equalization of ion thermal speeds can be achieved under suitable conditons (see Marsch, 1983, for a review).

The only attempt at incorporating all these effects into a solar wind model is that of Isenberg and Hollweg (1983) (see also Isenberg, 1983, 1984), who found that there are difficulties in explaining the preferential energization of heavy ions with reasonable assumptions concerning the spectrum of the waves.

Self-consistency is a difficulty in any solar wind model involving minor species, since the concentration of helium ions for example, is about 15–20% of that of protons by mass and this is not negligible. As a result of resonances, even tiny concentrations of minor species can affect wave propagation profoundly at the appropriate frequencies (e.g., Isenberg, 1983, 1984). Furthermore, simple three fluid models of the solar wind, excluding wave effects, suggest that the helium can play an important role in determining the detailed form of the solution even if its general nature is unchanged (e.g., Yeh, 1970; Joselyn and Holzer, 1978). Not surprisingly little progress has been made in carrying out a completely self-consistent treatment of the solar wind problem.

5. Termination of the Supersonic Solar Wind

Since the solar wind is supersonic it must, in order to adapt to the interstellar medium, be terminated by a shock wave beyond which the plasma flow is subsonic. It is possible to construct situations in which cosmic ray pressure gradients and loss of momentum resulting from charge-exchange with interstellar neutral gas can produce a smooth (transonic) transition to subsonic flow (Wallis, 1973). However, conditions must be rather special for this to happen if the overall pressure of the interstellar medium is finite.

If the effects of the solar magnetic field are neglected, the region of subsonic flow between the shock wave and the outer boundary of the heliosphere (or 'heliopause' – the interface between solar and interstellar plasma) would have almost constant pressure. In this case, the position of the shock wave can be determined by equating the dynamic pressure of the solar wind at the shock to the pressure of the interstellar medium just beyond the heliopause (see Axford, 1972, for a review). Thus

$$N_0 \overline{m} U_s^2 / R_s^2 = K P_g \,, \tag{12}$$

where N_0 is the solar wind number density at 1 AU, $\overline{m} = 2 \times 10^{-24}$ g is the mean mass of solar wind ions, U_s is the solar wind speed just within the shock position, R_s is the distance to the shock in AU, $K = 1.13$ for a strong shock and P_g is the total pressure of interstellar medium just beyond the heliopause. Ignoring to begin with the possible contribution from galactic cosmic rays, the main contributors to the total pressure of the interstellar medium at the heliopause are the pressure of the interstellar magnetic field (B_g) the pressure of the interstellar plasma and the dynamic pressure of the interstellar plasma, thus

$$P_g = \alpha B_g^2 / 8\pi + n_g (2kT_g + \overline{m} V_g^2) \,, \tag{13}$$

where n_g is the number density of the interstellar plasma, V_g is its speed relative to the Sun, and T_g its temperature. We have included a factor α to allow for the possibility that the magnetic pressure is enhanced as a result of being wrapped around the roughly spherical upstream face of the heliopause. For example, if the interstellar magnetic field direction is perpendicular to the relative velocity vector of the interstellar plasma with respect to the Sun it might be appropriate to take $\alpha = 2.25$.

It is not possible to measure the various quantities which determine P_g directly, but measurements of the dispersion and Faraday rotation of pulsar emissions can provide us with average values of n_g and B_g throughout a sphere of about 100 parsecs radius surrounding the Sun. Provided the interstellar medium within the sphere is fairly uniform these are the best values available, although the possibility of local variations cannot be excluded. Assuming that U_s has the same value as observed near the Earth, namely 400 km s^{-1} on average, that the flux is 2×10^8 cm^{-2} s^{-1} at 1 AU and that $\alpha = 2.25$, one can estimate a (minimum) value for R_s. For example, taking $V_g = 20$ km s^{-1} as suggested by observations of the neutral interstellar hydrogen, with $n_g = 0.05$ cm^{-2} and $B_g = 3 \times 10^{-6}$ G as suggested by pulsar observations, and with $T_g = 10^4$ K, we find from (12) and (13) that the minimum distance to the shock termination of the solar wind as a supersonic flow is about 100 AU. It is interesting to note that in this case the three components of P_g contribute in the ratio 81 : 14 : 40 so that the magnetic pressure is most important. Some observations of the relative velocity of the interstellar helium suggest that $V_g = 27$ km s^{-1} and if we were to assume this value, together with n_g and B_g unchanged, it is possible to argue that the shock might occur as close as 90 AU.

Recent observations by Kurth *et al.* (1984) suggest, on the basis of persistent radio emissions in the 2–3 kHz range observed from the Voyager spacecraft, that the shock termination occurs at a distance of 46 AU. The authors suggest that the radiation is emitted at the second harmonic of the plasma frequency corresponding to the density just behind the shock and that it penetrates in towards the Sun to a point where this is also the local plasma frequency in the solar wind. If this interpretation is correct the conclusion is important because it suggests that the shock will be encountered by Pioneer and Voyager spacecraft in a few years time. For the present, we are in the situation of being able to question the interpretation or of finding alternative explanations.

It is interesting to note that the plasma frequency of the interstellar medium lies in the range 1–3 kHz if the electron number density is 0.01–0.1 cm^{-2}. This suggests that the heliosphere, with the exception of the region around the Sun out to about 30 AU, is essentially a cavity surrounded by a medium in which such low frequency waves cannot easily propagate Accordingly, one would expect that waves originating anywhere within the cavity with frequencies below this cut-off frequency of a few kHz, would simply accumulate until their sources are balanced by losses due to damping or escape into the wake of the heliosphere. The intensity at a given frequency and also the upper cut-off frequency would be fairly constant unless observations are being made in the vicinity of possible sources such as interplanetary shocks. The characteristics of such a radiation field would be essentially independent of the distance to the shock wave terminating the supersonic solar wind and the inference made by Kurth *et al.* concerning its distance from the Sun would have to be abandoned.

Let us assume, however, that the shock termination indeed occurs at a distance of the order of 50 AU and seek possible explanations. This position for the shock wave could be achieved if the electron number density in interstellar space were as large as 0.3–0.4 cm^{-3}, or if the interstellar magnetic field strength were 12×10^{-6} G with $\alpha = 2.25$. However, with the pulsar values for these quantities and V_g = 20–30 km s^{-1}, to reduce R_s to less than 50 AU, it is necessary to find additional processes which either change the pressure balance condition or reduce the dynamic pressure of the solar wind (cf. Axford, 1973). It should be noted that we have in any case adopted fairly low values for the average solar wind speed and flux (e.g., Schwenn, 1983).

Although the plasma flow speed in the region between the shock wave and the heliopause is subsonic, it is not necessarily compressible nor must the total pressure be uniform, provided the magnetic field strength can build up appreciably. This will occur quite naturally even if the flow is strictly adiabatic and radial as shown by Axford (1972). However, with R_s = 50 AU, the heliopause would have to be at a distance of 100 AU or more for this effect to be appreciable. This distance is drastically reduced if the flow is non-radial so that magnetic flux tubes are evacuated of their plasma, and/or the flow is non-adiabatic as a result of charge-exchange between the initially 10^3 eV solar wind plasma and the 5 eV interplanetary hydrogen which permeates the region. As a consequence of these two effects, the magnetic field strength in the region must build up until at the heliopause the (solar) magnetic field pressure balances the total interstellar pressure, while at the shock wave the total pressure taken up by the solar wind dynamic pressure may be somewhat larger. The net result is a diminution of R by an amount of the order of d/R_s, where d is the thickness of the subsonic region in astronomical units; the diminution is perhaps 10–20%.

A second way of altering the pressure balance condition is to assume there is a so far undetected component of the galactic cosmic radiation which is either excluded from the heliosphere entirely or is unable to penetrate significantly within the shock. If these particles are excluded by the heliopause their pressure must simply be included in the pressure of the interstellar medium. If on the other hand they are able to penetrate the subsonic region but are effectively kept out of the region of supersonic solar wind flow the effect is the same as far as the relation (12) is concerned. Ip and Axford (1985) have estimated the spectrum of galactic cosmic-rays based on current ideas concerning their acceleration and have concluded that as a result of collisional losses and convective escape from the galaxy the spectrum falls off steeply at low energies and there is in fact no significant contribution to the interstellar pressure from (unobserved) low-energy cosmic rays. Most of the cosmic-ray pressure in this case is concentrated in the relativistic range where particles enter the supersonic region of the solar wind fairly freely so that the pressure balance condition is not directly affected. As pointed out most recently by Suess and Dessler (1985), if the (unmodulated) interstellar spectrum of galactic cosmic-rays continues to rise even fairly modestly in the unobserved subrelativistic range it is, ignoring any understanding we might have of the physics involved, possible to produce an interstellar pressure of the order of 6×10^{-12} dyn cm^{-2} necessary to bring the shock termination to the position inferred by Kurth *et al.* Whether or not the pressure of low-energy galactic cosmic-rays is indeed ten times that of relativistic cosmic-rays can only be determined by making the appropriate cosmic-ray measurements beyond 50 AU.

It is possible to reduce the distance to the terminating shock by modifying the ram pressure of the solar wind on the left-hand side of (12) (Axford, 1973). There are three ways in which this can be done. Firstly, the solar wind can be made to slow down by charge-exchange with interstellar neutral hydrogen atoms with penetrate freely to within about 4 AU of the Sun. The number density of the neutral hydrogen is observed to be not more than about 0.1 cm^{-2} and according to the radial flow model developed by Holzer (1972) this is sufficient to reduce the solar wind speed by about 15% at a distance of 50 AU without changing its flux. This translates to a 15% decrease of the solar wind dynamic pressure at the shock so that to bring the shock to this point would still require P_g to be substantially larger than we have considered reasonable. Secondly, the adverse pressure gradient of the (modulated) galactic cosmic-rays also tends to slow the solar wind down, again without changing the flux. However, a simple analysis, assuming that a cosmic-ray gradient of 1–2% AU^{-1} is maintained out to 50 AU, indicates that the diminution of the solar wind speed is only about 10% at the very most and so the requirement for a rather high interstellar pressure remains. The third effect, pointed out by Seuss and Dessler (1985), involves non-radial flow of the solar wind due to the fact that, if there is spherical symmetry near the Sun, the latitudinal pressure gradient of the interplanetary field deflects the solar wind away from equatorial regions at large distances, reducing the flux but maintaining U constant. According to these authors the effect is not more than 20% at $R = 50$ so that again it is not possible to avoid a fairly large value of P_g if the shock is to occur at this distance.

So many factors are unknown at present that it is unreasonable to make any hard and fast pronouncements. If the terminating shock occurs near 50 AU as inferred by Kurth *et al.* and this is confirmed by the Pioneer and Voyager spacecraft, measurements of cosmic-ray and solar wind parameters are likely to give an indication of the cause.

If not, the explanation that the radiation is trapped in the heliosphere cavity may have to be preferred.

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