IMPLICATIONS OF A WEAK TERMINATION SHOCK

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Abstract. Recent observations from the Voyager spacecraft have suggested that the spectrum of the anomalous cosmic ray component is relatively steep at the termination shock, which is believed to be responsible for accelerating these particles. This conclusion argues that the termination shock must be weak, which in turn requires that the upstream Mach number in the solar wind must be quite low, ~2.4. It is pointed out that such conditions are unlikely to prevail at all locations along the shock front. However, it is possible for such conditions to exist at the interface between high speed streams at high heliographic latitudes and the region at low latitudes where high and low speed streams have interacted and come into equilibrium. This discussion suggests a preferred location for the injection of the anomalous component into the shock acceleration process.

Key words: anomalous cosmic rays – solar wind – termination shock

1. Introduction

The purpose of this paper is to discuss the conditions in the solar wind immediately upstream from the termination shock. These conditions, of course, define the inner boundary condition for the interaction of the solar wind with the local interstellar medium – the subsequent shock transition, the subsequent downstream, subsonic flow, and the merging with the interstellar medium. We will undertake this discussion in the context of a recent set of observations and analysis by Stone *et al.* (1996) of the spectrum of the anomalous cosmic ray component at the termination shock, from which we can infer that the shock strength is weak, and therefore that the upstream Mach number is low. We will conclude that such conditions cannot prevail all along the shock front, but rather they may be unique to the interface region where high-speed streams at high heliographic latitudes interact with lower speed flow near the solar equatorial plane.

2. Implications of the Anomalous Component Spectrum

We begin by reviewing briefly the analysis of Stone *et al.* (1996) and the resulting implications of the observed spectra of anomalous cosmic rays for the strength of the termination shock. As was postulated by Fisk *et al.* (1974), the anomalous component is considered to originate as interstellar neutral gas that is swept into the heliosphere by the motion of the Sun relative to the local interstellar medium; this accounts for its anomalous composition of mainly helium, nitrogen, oxygen, and neon. Once here, it is ionized by charge-exchange and photoionization and becomes the pick-up ions, which have energies of ~1 keV/nucleon and which are now seen by the SWICS instrument on Ulysses (Gloeckler *et al.*, 1993). The pick-up ions are then convected outward by the solar wind into the outer heliosphere, and the prevailing theory, as postulated by Pesses et al. (1981), is that when they encounter the termination shock they are accelerated to high energies to form the anomalous cosmic ray component which is observed at energies of ~ 10's of MeV/nucleon, by, for example, the Voyager spacecraft (Stone *et al.*, 1996).

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The Voyager 1 spacecraft is now more than 50 AU from the Sun. It is a fairly straightforward calculation to estimate the spectrum of the accelerated anomalous particles, as it would appear at the termination shock, the distance of which is now estimated to be 70-90 AU from the Sun. The anomalous particles are singly charged – there is time to ionize the particles only once. They are thus of quite high rigidities, comparable to galactic cosmic rays with energies of ~ GeV/nucleon which do not experience much modulation in the solar wind. Equivalently, the extrapolation from the observed spectra at Voyager to the expected spectra at the termination shock is not large, and Stone *et al.* (1996) find the interesting result that the expected spectrum is quite steep – the intensity j varies with energy E as $j \propto E^{-\beta}$, with $\beta = 1.42 \pm 0.08$.

The theory for the acceleration of energetic particles at shocks is quite simple. Particles bounce back and forth across the shock front. They make head-on collisions with the magnetic irregularities on the upstream side, and they gain energy. They make over-taking collisions on the downstream side, and they lose energy. The upstream velocity is larger than the downstream one, and so the particles experience a net energy gain. Indeed, there is a simple formula, which relates the spectral index to the jump in flow speed of the plasma:

$$\frac{u_u}{u_d} = \frac{(2+2\beta)}{(2\beta-1)}. \tag{1}$$

Here, u_u and u_d is the upstream and downstream flow speed, respectively. This formula assumes only that the accelerated particles are in steady state, i.e. the number of particles and the flux of these particles, in a given velocity range, are conserved. This approach is also formally equivalent to assuming the particles gain energy by drifting through the electric field at the shock front. The work done by the shock electric field is identical to the work done by the solar wind on the pressure gradient of the pick-up ions, which is set up as they attempt to diffuse upstream from the shock front. It is quite unreasonable to assume that any one particle drifts undisturbed along the full length of the termination shock front. Rather, particles will be scattered off of and return to the shock many times where they experience diffusive or equivalently electric field acceleration, and the average behavior at any one location on the shock front should reasonably be described by (1).

With the value of $\beta = 1.42 \pm 0.08$ for the spectrum of the anomalous particles at the termination shock, the resulting flow speed jump is then found by Stone *et al.* (1996) from (1) to be $u_u/u_d = 2.63 \pm 0.14$. The termination shock can reasonably be assumed to behave as a simple gas dynamic shock since the expected ratio of the thermal pressure, due to the pick-up ions, to the magnetic pressure, is of order 10. The velocity jump is then related to the upstream Mach number by (e.g., Gombosi, 1994).

$$\frac{u_u}{u_d} = \frac{(\gamma+1)M_u^2}{2+(\gamma-1)M_u^2}. \tag{2}$$

where γ is the ratio of specific heats, or $\gamma = 5/3$. Thus, with $u_u/u_d = 2.63 \pm 0.14$, the upstream Mach number is found to be $M_u \approx 2.4$.

The termination shock could, of course, be a fairly complicated shock. As the anomalous particles are accelerated from low to high energies – from keV/nucleon to MeV/nucleon energies – they could exert a pressure force on the upstream solar wind, particularly the lower energy particles could exert such a force, which will slow down the solar wind before it reaches the shock front. There could be a fore shock region where the solar wind slows down adiabatically, followed by a fairly weak shock.

For the high energy anomalous particles, however, the detailed shock structure does not matter. These particles bounce back and forth across the shock front on relatively large spatial scales. The particles are quite mobile in the solar wind, otherwise they would not be seen with relatively little modulation at Voyager. The flow speed jump that these higher energy particles experience, then, from which they gain their energy and form their spectrum, is the total velocity jump. It does not matter whether the jump occurs in a fore shock region followed by a weak shock, or in a single shock jump.

If we stand back far enough from a shock, we can apply the Rankine-Hugoniot relations – mass, momentum, and energy must be conserved. Thus, if we are not interested in the details of the shock transition, just in the total speed jump, then (2), which is derived from the Rankine-Hugoniot relations, applies. Equivalently, if the total speed jump is only 2.6, the Mach number of the upstream solar wind, unaffected by the shock, must be only 2.4. Thus, if we believe the Stone *et al.* (1996) observations that the spectrum of the anomalous particles is steep ($\beta = 1.42$), and we believe that these particles are accelerated in a traditional shock acceleration model at the termination shock, then we are forced to conclude that the solar wind upstream from the shock front, and unaffected by the shock, has a very low Mach number.

There have been suggestions that galactic cosmic rays, which have fairly large pressures in the outer heliosphere, could affect the solar wind termination shock (Donohue and Zank, 1993). To have an influence on the solar wind, the cosmic rays must exert a pressure gradient. However, the pressure resides primarily in cosmic rays with energies of about 1 GeV/nucleon, which are quite mobile in the solar wind, and which typically have gradients of only a few percent per AU (e.g., Lockwood and Webber, 1993). There are, in fact, no significant pressure gradients in the galactic cosmic rays, and they exert little force on the solar wind.

3. Mechanisms for Yielding a Low Mach Number in the Outer Heliosphere

If the Mach number of the solar wind in the outer heliosphere is only ~2.4, we have to find a mechanism or mechanisms to develop a large internal pressure in the solar wind, perhaps through the use of the interstellar pick-up ions themselves, through some acceleration mechanism or instability, or by some proportional reduction in the solar wind flow energy. Consider several possibilities.

Left to its own devices, the steady solar wind is not much help. In a constant solar wind flow the internal pressure will cool adiabatically, the ram pressure will decline in proportion to density, and the Mach Number will go up dramatically. In a simple solar wind model, then, with no other processes involved, the Mach number of the solar wind in the outer heliosphere will be very large. Of course, there are other processes involved; in particular, the interstellar pick-up ions are continuously injected into the solar wind through the ionization of interstellar neutrals, and in the process of being picked up by the solar wind and subsequently isotropized, acquire a thermal energy equal to the solar wind flow energy. Indeed, the pick-up ions beyond about 10 AU from the Sun are the dominant internal pressure force in the solar wind (e.g., Holzer, 1977).

We can estimate how much pressure P should reside in the pick-up ions with the following equation:

$$u\frac{dP}{dr} + \frac{10}{3}\frac{u}{r}P = \beta_p n_n(r, \Theta)\frac{mu^2}{3}\frac{r_o^2}{r^2}. \qquad (3)$$

We assume that pick-up ions are injected into the solar wind with an ionization rate, β_p, at heliocentric radial distance $r_o = 1AU$. The pick-up ions are primarily hydrogen, so the ionization is due mainly to charge-exchange with the solar wind, the density of which varies as r^{-2}. The number injected is proportional to the interstellar neutral density n_n, which is a function of r and Θ, the angle between the solar wind velocity and the upstream direction of interstellar neutrals. We take n_n to be constant, which is a reasonable approximation in the outer heliosphere. The solar wind flow speed is u and the proton mass m.

Equation (3) is a direct consequence of the equation derived by Vasyliunas and Siscoe (1976) to calculate the expected distribution function of pick-up ions; (3) can be formed by taking the second moment of the Vasyliunas and Siscoe equation with respect to particle velocity, to form an equation for the pressure. The particles are assumed to be convected outward with the solar wind; they suffer adiabatic deceleration in the expanding solar wind; and there is continuous injection of new ions.

Equation (3) can be readily solved to yield:

$$P(r) = \frac{3}{7}\frac{r_o^2}{ur}\beta_p n_n \frac{mu^2}{3}. \qquad (4)$$

The average production rate of pick-up ions which is required to account for the observations of pick-up hydrogen as seen by Ulysses in the inner heliosphere is β_p = 7.5 x 10^{-7} $\sec^{-1}$ (Gloeckler *et al.*, 1993). The expected density of interstellar hydrogen is n_n = 0.08 cm^{-3}. A reasonable speed for the solar wind, near the equatorial plane in the outer heliosphere, is u = 455 km/s. With these values in (4), the average pressure of the pick-up ions at 80 AU, and thus the internal pressure in the solar wind at this distance is P = 0.075 eV/cm^3, consistent with more detailed calculations by Holzer (1977). The average solar wind density at $\sim$ 5 AU is observed to be $\sim$ 0.3 cm^3. Thus, the expected Mach number at 80 AU is $\sim$ 4.6. With pick-up ions alone, with no further acceleration, the average Mach number is a factor of two higher than the required value of $\sim$ 2.4. The Mach number goes as the square root of the pressure, or for the pick-up ions with no further acceleration to be responsible for the inferred low Mach number in the solar wind in the outer heliosphere, we would have to be off by a factor of 4 in their pressure, which appears to be unlikely.

Consider the possibility that the pick-up ions are accelerated through some interaction with the magnetic field or turbulence in the solar wind, and their pressure is increased. Indeed, the spectrum of pick-up ions seen near the equatorial plane in the inner heliosphere has a pronounced tail at speeds above twice the solar wind speed, the speed the particles can acquire through the pick-up process (Gloeckler *et al.*, 1994). This tail results, presumably, from acceleration of the pick-up ions in Co-rotating Interaction Regions, where high and slow solar wind flows interact, and which contain both shocks and extensive turbulence. Indeed, the pressure in the tail of the pick-up ion distribution can be comparable to or greater than the pressure in the initial pick-up ion distribution. Thus, should such acceleration continue into the outer heliosphere, then perhaps the pick-up ion pressure could be increased by the required factor of $\sim$ 4, and the Mach number lowered to $\sim$ 2.4.

The question arises, however, as to whether there is a sufficient energy source for such acceleration. The tail of the pick-up ion distribution in the inner heliosphere is produced by stream-stream interactions in the solar wind – high speed streams overtaking slower ones and producing shocks and turbulence. Such processes, however, diminish with increasing heliocentric distance. The solar wind near the equatorial plane tends to a nearly constant speed, with considerable variations in density and in the magnetic field strength (e.g., Belcher et al., 1987).

Indeed, the largest free energy source that is potentially available after stream-stream interactions come into equilibrium is the large scale variations in the magnitude of magnetic field which result from the piling up of solar wind material as the high speed flows overtake slower flows (e.g., Burlaga *et al.*, 1995). Magnitude variations in the magnetic field tend to be small in the solar wind on small spatial scales; the variations are Alfvénic in nature.

However, on large spatial scales the field magnitude can vary by a factor of order ~ 2, or the energy density varies by ~ 4.

Suppose, then, that it is possible to extract energy from the large magnitude variations in the solar wind magnetic field; perhaps the variations are not static, but propagating, and they can be damped by a transit-time damping mechanism (Fisk, 1976). If we consider that the energy in the fluctuations can be extracted with a characteristic damping length of 80 AU, then there is an additional term on the right side of (3), or

$$u\frac{dP}{dr} + \frac{10}{3}\frac{u}{r}P = \beta_p n_n(r,\Theta)\frac{mu^2}{3}\frac{r_o^2}{r^2} + 4\frac{u}{R}\frac{B_e^2}{8\pi}\frac{r_o^2}{r^2}. \qquad (5)$$

where $R = 80$ AU and B_e is the magnetic field strength at Earth. We assume that the field magnitude varies by a factor of 2, and the field is primarily azimuthal, i.e. that the energy in the field declines as r^{-2}.

Equation (5) can also be readily solved, and with $B_e = 3.5$ nT we find that the increase in the pressure in the pick-up ions due to the damping of the largest variations in the magnetic field that are available in the solar wind – the large-scale variations in the field magnitude – is only $\sim 10\%$. That is, acceleration of the pick-up ions is unlikely to be significant. This result is not surprising. The main source of energy for the pick-up ions is the flow energy of the solar wind. The particles, when they are first ionized, acquire the solar wind flow energy. Since the flow energy in the solar wind is so much larger than any internal energy in the solar wind (e.g., the magnetic field energy), it is not surprising that the pick-up ions acquire most of their energy through the initial pick-up process, and not by subsequent acceleration from the damping of waves or turbulence.

Equivalently, if we are to find a way to increase the internal pressure in the solar wind to where the Mach number is only ~ 2.4, it will be necessary to tap the flow energy of the solar wind. No other source is sufficient. Near the equatorial plane, access to the flow energy is difficult. High and low speed streams certainly interact near the equatorial plane and this converts flow energy into internal pressure. However, such interaction occurs in the inner heliosphere, and once completed, the flow stabilizes to a relatively constant flow speed, after which the pressure should tend to cool adiabatically and the Mach number tends to increase again.

There are, however, some possibilities at higher heliographic latitudes. Recall near solar minimum conditions the solar wind is fast and steady at high latitudes, flowing outward from the polar coronal holes with speeds of 700-800 km/s (e.g., McComas *et al.*, 1995). Near the equatorial plane, high and low speed streams interact and yield a steady flow at a lower speed of ~ 450 km/s. At some latitude, then, there must be an interface between this high speed flow and the lower speed flow. The interaction region near the equatorial plane may expand in latitude with increasing heliocentric distance – the conversion of flow energy into thermal pressure will drive an expansion in latitude – so that at each heliocentric radius there is a latitude where undisturbed high speed flow is encountering the lower speed flow. At this location the flow energy of the high speed flow is converted into internal pressure, and the Mach number of the high speed flow drops substantially. If this conversion of flow energy to internal pressure occurs relatively close to the termination shock, then in this location the Mach number of the solar wind upstream from the termination shock could have the required low value.

Consider a simple calculation. If we take the enthalpy per unit mass plus $u^2/2$ to be constant along a streamline, then a high speed flow with an initial speed of u_i and Mach number M_i will slow down to a final velocity and Mach number of u_f and M_f, subject to:

$$\frac{u_f^2}{u_i^2} = \frac{(3/M_i^2 + 1)}{(3/M_f^2 + 1)}. \qquad (6)$$

Thus, if the initial Mach number is M_i = 4.6, as is expected in the outer heliosphere with the large pick-up ion pressure, and the required final Mach number is M_f =2.4, then, from (6) the speed of the high speed flow must be reduced to u_f/u_i = 0.86. Such a reduction is not unreasonable in that a high speed flow of 750 km/s, colliding with a slower 450 km/s flow and coming to rest at the speed of the center of mass of these two flows, would have its speed reduced by approximately this amount.

It would appear then that it is possible to have the required Mach number upstream from the termination shock of $\sim$ 2.4 at a specific location, viz. at latitudes above the equatorial plane where high and low speed streams are actively interacting in the outer heliosphere. At lower latitudes, the interaction occurs in the inner heliosphere, and although the Mach number is reduced by the interaction, the subsequent expansion of the solar wind will tend to increase the Mach number again. At higher latitudes, the high speed flow persists all the way out to the termination shock, and the Mach number remains high. This suggestion that there is an intermediate latitude range where the Mach number of the solar wind is small requires, of course, that the interaction region of high and low speed flows near the equatorial plane does not expand rapidly with latitude, and enclose the heliosphere at relatively small heliocentric distances. It is necessary to preserve the high speed flow at these intermediate latitudes to large heliocentric distances, $\sim$ 80 AU, and to have the interaction with the lower speed flow occur at this location, immediately upstream from the termination shock.

We should ask, of course, whether the anomalous cosmic rays seen by Voyager could in fact have originated from this intermediate latitude range, where we might expect a low upstream Mach number and a weak termination shock. Indeed, that could be the case. Gradient and curvature drifts, and diffusion, during this portion of the solar magnetic cycle are expected to be inward in radial distance, and downward in latitude (e.g., Jokipii et al., 1977). The anomalous particles seen by Voyager should thus have originated at a higher latitude and a larger heliocentric distance, which is not inconsistent with a location on the termination shock where the upstream Mach number could be low.

It is also interesting to note that the interface between the high speed flow at higher latitudes, and the lower speed flow near the equatorial plane has a large velocity shear, $\sim$ 350 km/s, and could be Kelvin-Helmholtz unstable. The magnetic fields in the high and lower speed flows have different origins at the Sun, and thus do not cross the interface, nor tend to suppress the instability. This instability could be responsible for reducing the speed of the high speed flow, and thus for converting flow energy into internal pressure. It could also be responsible for accelerating the pick-up ions in advance of the termination shock. One of the difficult problems for accelerating the pick-up ions at the termination shock is to provide a mechanism for their injection into the shock acceleration process. The pick-up ions have thermal speeds comparable to the solar wind speed. It is difficult for such particles to propagate upstream in the solar wind, particularly when the magnetic field is highly azimuthal as it is in the outer heliosphere. Such particles might thus be expected simply to be convected through the shock front, and not to bounce back and forth and experience the energization envisioned in (1). However, if such particles are pre-accelerated, in advance of the shock, the injection is then straight-forward. A Kelvin-Helmholtz instability is a Venturi effect. It creates pressure variations in the flow, which could result in variations in the magnetic field strength. Such variations could provide a natural acceleration of the pick-up ions through a magnetic pump mechanism.

Finally, we note that if this explanation is correct, there are some interesting implications for the solar cycle dependence of the Mach number at the termination shock. The polar coronal holes expand as the solar cycle evolves towards solar minimum. The interface, then, where high and slower speed flows interact in the outer heliosphere, upstream from the shock, will then move downward in latitude as we approach solar minimum, and retreat as conditions evolve towards solar maximum. With regard to acceleration at the termination shock, it is reasonable to expect that particles are accelerated everywhere along the shock front since drift motions will carry the particles to all latitudes, following their injection even from a preferred location near the high and slower speed flow interface. However, the behavior of the spectral shape of the accelerated particles at the shock front with latitude should vary during the solar cycle, which may be reflected in the intensity of anomalous particles seen near the equatorial plane, or by Ulysses at high latitudes.

4. Summary

In summary, there are interesting observations by Stone *et al.* (1996) which suggest that the spectrum of the anomalous cosmic rays appears to be steep at the termination shock, which, in turn, suggests that the total jump in velocity at the shock is relatively small. This can occur only if the upstream Mach number is only of order 2.4. When we consider how the Mach number could be so low, the only viable mechanism is the conversion of solar wind flow energy into internal pressure. Near the equatorial plane, such conversion occurs at relatively small heliocentric radial distances (within $\sim$ 20 AU of the Sun), as high and low speed solar wind flows interact, after which the Mach number will tend to increase again. The only possibility appears to be to perform this conversion at higher latitudes where the high speed streams, at least near solar minimum conditions, may be preserved into the outer heliosphere, and then slow down by interacting with slower speed flow that has expanded upward in latitude from the equatorial region. It may also be possible that the interface between the lower speed flow near the equatorial region, and the high speed flow at high latitudes is Kelvin-Helmholtz unstable. The termination shock that follows this region of low Mach number would be an ideal candidate for the acceleration of the anomalous component because the effects of the Kelvin-Helmholtz instability could be to pre-accelerate the pick-up ions, and readily inject them into the shock acceleration process. These arguments suggest that the entire termination shock is not weak, but rather it can be weak only in the mid-latitude region, with the remaining shock conforming to the usual expectations that it is strong and embedded in a relatively high Mach number flow.

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References

Belcher, J.W., Lazarus, A.J., McNutt, R.L, Jr., and Gordon, G.S., Jr.: 1993, *J. Geophys. Res.* **98**, 15177.

Burlaga, L.F., Ness, N.F., and McDonald, F.B.: 1987, *J. Geophys. Res.* **92**, 13647.

Donohue, D.J., and Zank, G.P.: 1993, *J. Geophys. Res.* **98**, 19005.

Fisk, L.A., Kozlovski, B., and Ramaty, R.: 1974, *Astrophys. J.* **190**, L35.

Fisk, L.A.: 1976, *J. Geophys. Res.* **81**, 4633.

Gloeckler, G., Geiss, J., Balsiger, H., Fisk, L.A., Galvin, A.B., Ipavich, F.M., Ogilvie, K.W., von Steiger, R., and Wilken, B.: 1993, *Science* **261**, 70.

Gloeckler, G., Geiss, J., Roelof, E. C., Fisk, L. A., Ipavich, F. M., Ogilvie, K.W., Lanzerotti, L.J., von Steiger, R., and Wilken, B.: 1994, *J. Geophys. Res.* **99**, 17637.

Gombosi, T.I.: 1994, in *Gaskinetic Theory,* Cambridge University Press, 266.
Holzer, T.E.: 1977, *Rev. Geophys. Space Phys.* **15**, 467.
Jokipii, J.R., Levy, E.H., and Hubbard, W.B.: 1977, *Astrophys. J.* **213**, 861.
Lockwood, J.A., and Webber, W.R.: 1993, in *Proc. 23rd Int. Cosm. Ray Conf.* (Calgary) **3**, 469.
McComas, D.J., Phillips, J:L., Bame, S.J., Gosling, J.T., Goldstein, B.E., and Neugebauer, M.: 1995, *Space Sci. Rev.* **72**, 93.
Pesses, M.E., Jokipii, J.R., and Eichler, D.: 1981, *Astrophys. J.* **246**, L85.
Stone, E.C., Cummings, A.C., and Webber, W.R.: 1996, *J. Geophys. Res.* **101**, 11017.
Vasyliunas, V.M., and Siscoe, G.L.: 1976, *J. Geophys. Res.* **81**, 1247.