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ON THE RELATIONSHIP BETWEEN COLLISIONLESS SHOCK STRUCTURE AND ENERGETIC PARTICLE ACCELERATION

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1. Introductory Remarks

In this review, we attempt to synthesize recent experimental research on bow-shock structure and theoretical studies of quasi-parallel shock structure and shock acceleration of energetic particles, to point out the relationship between shock structure and particle acceleration. In Section 2, we discuss the phenomenological distinction between quasi-parallel ($Q_{\parallel}$) and quasi-perpendicular ($Q_{\perp}$) shocks that has emerged from bow-shock research, and review present efforts to extend this work to interplanetary shocks. In Section 3, we summarize existing theories of $Q_{\parallel}$ shock structure. In Section 4, we turn to theories of particle acceleration by shocks. In Section 5, we discuss attempts to relate particle acceleration to shock structure using multiple fluid models. We synthesize the broad conclusions drawn from the discussions in Sections 2 - 5 in Section 6. Section 7 concludes our review with a few general remarks.

2. Observational Distinction Between $Q_{\parallel}$ and $Q_{\perp}$ Shocks

Earth bow-shock studies have revealed a profound difference between $Q_{\parallel}$ and $Q_{\perp}$ shocks (Formisano, 1977; Greenstadt and Fredericks, 1979). The shock normal angle θ_{Bn} separates the two types; $Q_{\perp}$ shocks have $\theta_{Bn} \gtrsim 45°-55°$, and vice versa for $Q_{\parallel}$ shocks. Quasi-perpendicular shocks are about an ion Larmor radius thick (Leroy et al., 1981; Livesey et al., 1982), as measured by jumps in both the magnetic field and plasma density. On the other hand, in $Q_{\parallel}$ shocks, the magnetic field undergoes a much broader and more disorderly transition whose spatial scale is difficult to determine from bow-shock measurements

(NASA-CR-175328) ON THE RELATIONSHIP BETWEEN COLLISIONLESS SHOCK STRUCTURE AND ENERGETIC PARTICLE ACCELERATION (California Univ.) 18 p HC A02/MF A01 CSCL 20H
N84-15909
Unclas
G3/72 11389

(Greenstadt et al., 1982b). It is not known whether there is a thin density jump embedded within the broad region of large-scale magnetic turbulence that characterizes $Q_{\parallel}$ shocks.

The facts that $Q_{\parallel}$ shocks allow significant access upstream of particles that have interacted with the shock, while $Q_{\perp}$ shocks do not, appear to be the primary observational distinction between the two. As early as 1968, we knew that the solar wind can have foreknowledge of an impending bow-shock crossing when it is connected magnetically to the shock (Asbridge et al., 1968; Fairfield, 1969). The connected region of upstream disturbance has come to be known as the foreshock. The interplanetary field line that is instantaneously tangent to the curved bow-shock surface defines the leading edge of the foreshock; at the point of tangency, the shock normal angle θ_{Bn} is 90°. Near the point of tangency, the locally $Q_{\perp}$ shock evidently accelerates electrons (K. Anderson, 1968, 1968; Feldman et al., 1973, 1983; K. Anderson et al., 1979; R. Anderson et al., 1981) and ions (Gosling et al., 1978, 1979, 1980; Greenstadt et al., 1981) into thin, focused beams which escape upstream along field lines. When they are observed upstream, the beams may be traced kinematically back to the $Q_{\perp}$ shock (Greenstadt, 1976), and the faster electron beam is encountered upstream of the ion beam. The upstream electron and ion distributions become progressively more diffuse downstream of their beam leading edges, on field lines that connect to a bow shock that is more and more $Q_{\parallel}$ (K. Anderson et al., 1979; Gosling et al., 1978; Greenstadt et al., 1980; Bonifazi et al., 1980; Bonifazi and Moreno, 1981; Eastman et al., 1981; Paschmann et al., 1981; Feldman et al., 1982).

The superthermal particles in the foreshock generate a rich spectrum of magnetohydrodynamic and plasma waves (Scarf et al., 1970, 1971). Escaping electrons generate electron plasma waves (Scarf et al., 1971; R. Anderson et al., 1981), low-frequency (∿1 Hz) whistler waves (Feldman et al., 1983; Sentman et al., 1983), and higher-frequency whistlers (Fairfield, 1974). Ion acoustic waves are associated with superthermal ions and electrons in the foreshock (Scarf et al., 1971; Rodriguez and Gurnett, 1975; R. Anderson et al., 1981; Parks et al., 1981). Low frequency magnetohydrodynamic waves are associated with the upstream ion beam (Hoppe et al., 1982). Hydromagnetic waves achieve large amplitudes in the diffuse proton zone (Paschmann et al., 1979; Greenstadt et al., 1980; Hoppe <u>et al.</u>, 1981).

The impressive clarification of foreshock phenomenology achieved in the last decade has not improved our fundamental understanding of the difference between $Q_\perp$ and $Q_\parallel$ shocks because of an ambiguity inherent in the interpretation of terrestrial foreshock measurements. It has been argued that many, perhaps most, of the diffuse ions come from the ion foreshock beam (Bame <u>et al.</u>, 1981a; Bonifazi and Moreno, 1981). As such beam ions propagate upstream, they destabilize low-frequency electromagnetic waves which subsequently scatter and decelerate them. The decelerated ions and the waves are blown downstream by the solar wind to fill the entire foreshock with waves and diffuse ions. The waves are ultimately blown back into the quasi-parallel zone of the shock surface, possibly accounting for the disordered magnetic structure of $Q_\parallel$ shocks. In this interpretation, the $Q_\parallel$ bow-shock structure we observe is an artifact of the small radius of curvature of the bow shock. On the other hand, one can argue that some shock-heated ions ought to escape naturally from plane $Q_\parallel$ shocks (Edmiston <u>et al.</u>, 1982; Tanaka <u>et al.</u>, 1983). In this case, some of the foreshock phenomena we observe might be inherent to $Q_\parallel$ shocks. Whatever the situation, the curvature of the bow shock does alias the results, so that it is impossible to assign uniquely the phenomena observed upstream to a given shock normal angle.

The upstream superthermal ion energy density is comparable with that of the interplanetary field, and, more significantly, the solar wind is decelerated and deflected when it enters the foreshock (Bonifazi <u>et al.</u>, 1980) by an amount compatible with the momentum flux carried by shock-escaping ions (Bame <u>et al.</u>, 1980; Sentman <u>et al.</u>, 1981a). Thus, part of the shock transition is accomplished in the foreshock, and the overall thickness of the $Q_\parallel$ part of the bow shock therefore exceeds its radius of curvature.

It is much more difficult to determine the true extent of $Q_\parallel$ shocks from the bow-shock than from interplanetary shocks, whose radii of curvature are 25-2500 times that of the bow shock. At present, the search for interplanetary foreshock phenomena is incomplete. To ascertain whether $Q_\parallel$ interplanetary shocks have foreshocks, one should begin by comparing measurements made at equal distances upstream of interplanetary shocks and the bow shock. This implies searching for foreshock signatures a few tens of seconds before an interplanetary shock encounter, when the high-speed shock is a few earth radii from the spacecraft. Kennel et al. (1982) found that the amplitude and spectrum of ion acoustic waves a few earth radii ahead of interplanetary shocks are remarkably similar to those observed at the same distance from the bow shock. These ion acoustic waves extended several hundred earth radii ahead of $Q_{\parallel}$ interplanetary shocks, the first indication that foreshocks might be much larger than is possible to infer from bow-shock studies (Kennel et al., 1982). It is of obvious interest to inquire whether other phenomena characteristic of the earth's foreshock also occur far upstream of interplanetary $Q_{\parallel}$ shocks. Russell and Hoppe (1982), Russell et al. (1983), and Tsurutani et al. (1982, 1983) have recently found hydromagnetic waves, whose amplitudes and frequencies are similar to those in the earth's foreshock, ahead of $Q_{\parallel}$ interplanetary shocks. Gosling et al. (1983) have also found evidence of diffuse superthermal ions upstream of some interplanetary $Q_{\parallel}$ shocks. Thus, at least three features characteristic of the earth's foreshock also occur upstream of $Q_{\parallel}$ interplanetary shocks.

3. Theories of $Q_{\parallel}$ Shock Structure

Let us now survey the development of our theoretical ideas concerning the structure of quasi-parallel shocks. It has been popular to separate the structure into a local shock layer and a larger "upstream" region in which part of the shock dissipation required by the Rankine-Hugoniot conditions is accomplished. It is in the upstream foreshock that the processes thought responsible for energetic particle acceleration occur. In general, laboratory and space plasma theoreticians have concentrated on the subshock and the near foreshock, and cosmic ray and astrophysical plasma theorists have focused on the foreshock and neglected subshock structure.

Parker (1961) first recognized implicitly the role of escaping ions in $Q_{\parallel}$ shocks, when he argued that parallel ion beams would be firehose unstable and thereby produce large-amplitude Alfvèn turbulence that accomplishes the shock transition on a scale of many ion Larmor radii. Moiseev and Sagdeev (1963) developed a parallel shock model in which upstream ions could be reflected from an ion acoustic potential structure would no longer exist. They then argued that turbulent heating would produce a firehose unstable anisotropy if the upstream plasma β

were sufficiently high. This suggestion motivated Kennel and Sagdeev (1967) and Kennel and Petschek (1968) to develop a theory of low Mach number, parallel firehose shocks in high β plasmas. Auer and Volk's (1973) numerical calculation subsequently confirmed the general outlines of firehose shock theory. These models failed to recognize the importance of Parker's (1961) suggestion by not including the effects of escaping upstream ions. Kennel (1981) suggested that a fusion of the ion heat-flux and anisotropy firehose models might be promising.

The above models considered only the long-wavelength limit of the firehose instability, where it is non-resonant. On the other hand, the same mode is resonant for wavelengths near the ion Larmor radius, or when the plasma β is less than unity (Kennel and Scarf, 1968). Recent work on the resonant anisotropy instability has focused on the foreshock and not on the subshock. Gary (1981), Gary et al. (1981), and Sentman et al. (1981b) showed that the ions measured upstream of the terrestrial subshock are unstable to the resonant instability and, when conditions are appropriate, to the non-resonant instability as well. It is generally believed that the upstream ions do generate the large-amplitude, low-frequency waves in the earth's foreshock, as Barnes (1970) first suggested.

Lee's (1982) self-consistent theory for the decay of an ion beam escaping from the bow shock invokes resonant quasi-linear scattering by low-frequency electromagnetic waves and the subsequent energization of ions by scattering and shock compression. In this theory, the deceleration of the escaping superthermal ions and their subsequent energization are both consequences of turbulence generated by pitch-angle anisotropies. Lee (1983) extended his bow-shock theory to the interplanetary case and applied it to the interplanetary shock that occurred on November 11-12, 1978. Starting with Scholer et al.'s (1983) measured 30 keV/Q ion intensity, he was able to account for their particle measurements at higher energy and to predict a wave amplitude and spectrum, which are in good agreement with observation (Kennel et al., 1983a, 1983b).

Numerical simulations have contributed substantially to quasi-parallel shock theory. Because of the limitations of spatial scale, numerical simulations treat only the subshock. Biskamp and Welter (1972) proposed an electrostatic, rather than electromagnetic, ion beam instability as the dissipation mechanism for the strong quasi-parallel shock they simulated. Recent 2-D simulations (Quest et al., 1983) found that large-amplitude whistler turbulence on the ion inertial scale length is generated in $Q_{\parallel}$ shocks, and that intense fluxes of ions are reflected upstream. Kan and Swift (1983) simulated $Q_{\parallel}$ shocks in one dimension but over a long spatial scale. They found that a whistler wave train standing upstream of the shock resonantly scatters incoming ions, and that long wavelength non-resonant firehose modes are created downstream.

In summary, nearly all theories of $Q_{\parallel}$ shock structure agree that large-amplitude magnetic turbulence, with frequencies that span the range from well below to somewhat above the ion cyclotron frequency, is central to the dissipation in the plasma subshock and to the dynamics of the foreshock ahead of it.

4. Shock Acceleration of Energetic Particles

Until recently, most theories of cosmic ray acceleration concentrated on elucidating how single particles can attain high energy by single or multiple encounters with collisionless shocks which are considered to be infinitely thin and whose plasma structure is therefore assumed to be relatively unimportant. Looked at in this fashion, shocks can accelerate particles in several ways. Ions whose Larmor radius exceeds the shock thickness conserve their gyrophase averaged magnetic moment (E. N. Parker, unpublished manuscript, 1958; Chen and Armstrong, 1972; Shabanskii, 1962; Pesses, 1979; Terasawa, 1979a,b). Such ions approaching the shock from upstream would therefore be either reflected from or transmitted through the jump in magnetic field and potential at the shock, depending upon their pitch angle. Reflected ions grad-B and curvature drift parallel to the flow electric field and thereby acquire energy, the more efficiently the more quasi-perpendicular the shock (Sonnerup, 1969). However, since multiple reflections are needed to account for the observed acceleration by interplanetary shocks (Pesses, 1979), reflected ions must be scattered from upstream MHD turbulence back towards the shock. They then can be either re-reflected or retransmitted at their next encounter with the shock. Re-reflected particles can repeat the above cycle, and some can reach high energy.

Energetic particles that are transmitted through the shock can be scattered by downstream magnetic turbulence back toward the shock. Such particles are subject to first-order Fermi-acceleration by multiple reflections between upstream and downstream waves that convect approximately with the local flow speed. The shock then serves primarily to decelerate the flow so that the scattering centers appear to converge toward one another in the shock frame. In the test particle limit, this mechanism does not take into account the momentum transfer between cosmic rays and the plasma. The integral spectrum for particles Fermi-accelerated by infinite plane shocks depends only upon the ratio of upstream and downstream flow speeds (Krimsky, 1977; Axford et al., 1977; Bell, 1978a,b; Blandford and Ostriker, 1978; Lee, 1982, 1983). Because the calculated spectral index is close to the observed galactic cosmic ray index, supernova shocks are promising candidates to accelerate galactic cosmic rays (Axford, 1981).

For the solar system, the theory of first-order Fermi-acceleration has been applied to the diffuse ions upstream of the bow shock (Terasawa, 1979, 1981; Eichler, 1981; Lee et al., 1981; Forman, 1981; Ellison, 1981; Lee, 1982), and the so-called interplanetary ESP events, in which energetic ions are observed to increase well before the shock encounter (Scholer and Morfill, 1975; Scholer et al., 1983; Lee, 1983). Lee's (1982) theory predicts the energy spectra of different species reported by Ipavich et al. (1981) and the spectrum and amplitude of the low-frequency waves observed upstream of the bow shock by Hoppe et al. (1981) and others. The observed spectrum of bow-shock diffuse particles cuts off above about 100 keV, a fact which may be explained by the finite extent of the bow shock. Either a given magnetic field line remains connected to the region where the bow shock is strong for a finite time, or the particles diffuse across the magnetic field onto field lines which no linger interact with the shock (Eichler, 1981; Skadron and Lee, 1982). Either effect limits the number of shock crossings a particle can have and, therefore, the energy to which it can be accelerated.

The field line connection time is much larger for interplanetary shocks than for the bow shock, so the first-order Fermi mechanism will have longer to operate. The energetic ion fluxes theoretically should increase exponentially approaching a steady, planar shock, maximize at the shock, and hold approximately constant downstream--features characteristic of ESP events. The accelerated ions should be essentially isotropic in the shock frame upstream and isotropic in the solar wind frame downstream.

There have been relatively few measurements of moderate energy ions in ESP events in the energy range (tens of keV) that bridges the low-energy plasma and "seed" particles (see Section 6) and high-energy cosmic rays (however, see Lin et al., 1974; Gosling et al., 1980, 1981; and Gosling, 1983). A recent study of 30-150 keV/Q protons and alphas in three ESP events (Scholer et al., 1983) finds that the particle energy and angular distributions and spatial profiles are consistent with first-order Fermi-acceleration theory.

5. Relation of Subshock Structure and Foreshock Particle Acceleration

E. N. Parker was one of the first to realize that if interstellar shocks accelerate the observed galactic cosmic rays, cosmic rays must have sufficient energy density to contribute to shock structure. The test particle limit may therefore be misleading. Wentzel (1971), Axford et al. (1977, 1982), and Drury and Volk (1981) included the pressure, but not the number and momentum densities, of the cosmic rays in the calculation of gas-dynamic shock structure. Cosmic rays were assumed to diffuse spatially with a long characteristic scale length, and the thermal plasma was assumed to be subject to unspecified dissipation due to microturbulence. These calculations retrieve the gas-dynamic jump conditions when no energetic particles are present. On the other hand, if the upstream cosmic ray pressure is non-zero and the sonic Mach number exceeds about 10, the entire shock transition takes place in the cosmic rays without a discontinuity in the thermal plasma. For lower Mach numbers, there must be both a cosmic ray foreshock and a plasma subshock--the situation which should pertain to the shocks typically encountered in the solar system. Given the upstream particle pressure, these two-fluid models produce an estimate of the downstream energetic particle pressure, and thus the efficiency, of particle acceleration. McKenzie and Volk (1982) included the Alfvén waves that scatter the energetic particles as a third fluid in the shock-structure calculation. Inclusion of the waves reduces the downstream energetic particle pressure; moreover, the spatial profile of the foreshock depends on whether the waves remain quasi-linear or saturate nonlinearly. Since the above theories treat energetic particles as a fluid, they cannot calculate the spectral index of the energetic particle distribution. Existing kinetic calculations that do calculate a spectral index neglect the deceleration of the upstream flow by the energetic particles, and so a fully self-consistent kinetic treatment of a foreshock-subshock system remains to be done.

6. Toward a Unified View of Shock Structure and First-Order Fermi-Acceleration

Four major conclusions emerge from the discussion in this review:

- Only $Q_{\parallel}$ shocks have the extended regions of MHD turbulence upstream and downstream that are the essential ingredients of the first-order Fermi-acceleration scenario. This fact may be related to the ease with which not only energetic cosmic rays, but also particles on the tail of the thermal distribution, can free stream across $Q_{\parallel}$ shocks.

- Quasi-parallel shocks consist of a foreshock and a plasma subshock. Part of the change in plasma conditions required by the Rankine-Hugoniot relations is effected by energetic particle scattering in the foreshock.

- It may be possible to accomplish the entire foreshock-subshock transition with low-frequency electromagnetic waves as the dominant scattering mechanism. The theories for resonant scattering of foreshock superthermal and energetic particles (Lee, 1982, 1983) and for plasma thermalization (Parker, 1961; Kennel and Sagdeev, 1967; Kennel and Petschek, 1968; Auer and Volk, 1973) all invoke long-wavelength electromagnetic waves destabilized by pitch-angle anisotropy. Even the thermalization of incoming plasma ions by standing whistlers (Quest et al., 1983; Kan and Swift, 1983) is a variation on the same theme.

- The energetic-particle spectrum generated by a steady plane shock depends only on the jump in plasma velocity across the shock. In general, the spectral index will also depend upon the geometry and time evolution of the shock. (Forman, 1981)

Before we can arrive at a comprehensive theory that, among other things, computes the cosmic ray intensity and spectrum as a function of shock parameters, we must understand how particles that are originally part of the thermal plasma reach the energy threshold where Fermi-acceleration begins to operate. Present energetic particle diffusion calculations start with a source of "seed" particles which can either be in the upstream flow or be injected at a subshock. It matters not for the final spectral index whether the seed particles are injected far upstream (Axford et al., 1977; Blandford and Ostriker, 1978) or at the subshock (Lee, 1982, 1983). However, the energetic particle intensity will clearly depend upon the strength, and thus the location, of the source.

As it is unsatisfying to rely upon a pre-existing flux of cosmic rays upstream, it is encouraging that at least those shocks with subshocks appear to inject seed particles into the foreshock. Theoretically, it is clear that the seed particles at one time must have been thermal ions that interacted with the subshock once on their way to participating in the Fermi process. In the case of the bow shock, these are the few keV "upstream" or "superthermal" ions that were reflected from or transmitted through the shock. There has been only one study of the interplanetary shock analogs of upstream particles (Gosling et al., 1983). Eichler (1979) and Ellison (1981), arguing that the terms "thermal", "seed", and "energetic" are artificial verbal distinctions, developed a shock-structure model in which all ions interact with electromagnetic waves in essentially the same way to produce a scattering mean free path at each energy that is proportional to the Larmor radius. Such a diffusion model efficiently produces a high-energy tail that blends smoothly with the thermal distribution.

7. Concluding Remarks

Although theoretical models of quasi-parallel shocks are over 20 years old, and although the suggestion that energetic particles are significant to shock structure is equally venerable, experimentalists could do little with these ideas until the past five years. The earth's foreshock has a complex phenomenology whose disorder had to be reduced before it could be fitted into a theoretical framework that had once seemed peculiarly ill-adapted to bow-shock observations. Now, it is clear that quasi-parallel shocks have such an enormous spatial scale that interplanetary shocks are a better experimental arena to test theories of their structure.

A coherent viewpoint is now emerging from the experimental and theoretical research of the past five years. Only quasi-parallel shocks have the large regions of magnetohydrodynamic turbulence upstream and downstream that is the essential ingredient for first-order Fermi-acceleration of energetic particles. It appears that superthermal and energetic particles can stream freely through quasi-parallel shocks, and that such particles generate the wave-fields that scatter them.

The outlines of a theory that will eventually predict the intensity and spectrum of shock-accelerated particles as a function of shock parameters and time evolution are in view. That said, it is prudent to add two cautionary warnings. First, not much is known about the microstructure of quasi-parallel shocks, or even whether they have a microstructure. The current theoretical models are based on the interactions between particles and electromagnetic waves with wavelengths equal to or longer than a thermal ion Larmor radius. While it is conceivable that they could account both for the shock dissipation and energetic particle scattering, it is not proven that they can do so uniquely. Second, our experience with the earth's bow shock indicates that shock structure is strongly parameter-dependent, so that the picture of the large-scale quasi-parallel shock structure that has emerged from the few interplanetary shock studies completed to date might be misleading. It remains for future research to confirm, or to temper, our present enthusiasm.

Acknowledgments

It is a pleasure to thank my numerous co-authors on our papers on the interplanetary shock of November 11-12, 1978 (Kennel et al., 1983a, 1983b) with whom I have had many illuminating discussions about the topics in this review. This work was supported at UCLA by NASA NGL-05-007-190 and at TRW by NAS-5-20682.

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