SHOCK WAVES, PARTICLE ACCELERATION AND NON-THERMAL EMISSION

R. D. Blandford
130-33 Caltech
Pasadena, California 91125, U.S.A.

Abstract: Some recent developments in the theory of particle acceleration at supernova shock fronts are reviewed and the confrontation of this theory with measurements of galactic cosmic rays and observations of supernova remnants is discussed. Supernova shock waves are able to account for the energetics, spectrum and composition of galactic cosmic rays, though it remains difficult to understand acceleration of $\sim 10^5$ GeV particles. Recent developments in the analysis of interplanetary shock waves and in the numerical simulation of quasi-parallel shocks are encouraging. Interpretations of different categories of remnants are reviewed and a speculative interpretation of the optical companion to SN1987a is discussed.

Introduction: The primary interaction of an expanding supernova remnant with the interstellar medium is mediated by the bounding shock front. For most astronomers this shock front can be treated as a discontinuity—a sort of Dedekind cut separating the unshocked gas from higher entropy shocked gas in thermal equilibrium at some temperature T whose subsequent evolution is to be modelled. This is not the view of a plasma astrophysicist for whom high Mach number collisionless shock waves possess structure that has to be understood prior to analysing the downstream flow. In this talk I shall discuss this structure.

The interstellar medium has several distinct components. The substrate is the thermal plasma and, as is well known, a strong shock wave moving with speed $V_s = 1000 V_{s8}$km s^{-1} will, according to the Rankine-Hugoniot conditions, quadruple its density and increase its temperature to $T = 1.4 \times 10^7 V_{s8}^2$K. However, this temperature is really only a measure of the rms thermal ion speed. There is every expectation that a collisionless shock will not transmit electrons and ions with the same temperature and indeed a Maxwellian distribution function is not guaranteed. Suprathermal tails of electrons and ions are created at shocks and can persist in the face of Coulomb collisions, probably bolstered by wave damping. This may invalidate existing analyses of optical and X-ray line strengths which generally assume a Maxwellian electron distribution and often at the same temperature as the ions. (Aschenbach, Kirshner, this volume). The interaction of dust grains with shock fronts has important implications for the IR emission, which may be the dominant radiative loss from an expanding remnant (Dwek, this volume).

However, in this talk I shall be mostly concerned with the interaction of cosmic rays and magnetic fields with shocks. In the following two sections, I shall summarise what is generally understood about non- thermal processes in supernova remnants. I shall then describe some more recent developments in the study of collisionless shocks. Finally, I shall return to the interpretation of observations of supernova remnants and suggest some specific investigations which should now be practical. Recent reviews of this

https://doi.org/10.1017/S025292110010257X Published online by Cambridge University Press

and associated topics can be found in Blandford (1982) Drury (1983), Kennel, Edmiston and Hada (1985), Blandford and Eichler, (1987).

Acceleration of Galactic Cosmic Rays: Galactic cosmic rays are observed with kinetic energy T from 1 to 10^{11}GeV. The differential number spectrum from $\sim 5 - 10^5$GeV is a power law with logarithmic slope ~ 2.7 for the primary particles (*e.g.*p, C, O) and slope ~ 3.1 for the secondaries (*e.g.*Li, Be, B) created by spallation in the interstellar medium. The secondary spectrum tells us that $\sim$ 5GeV primary particles traverse a grammage $\lambda_e \sim 7$g cm^{-2} which declines $\propto T^{-0.4}$ at higher energy. From this we infer that the source spectrum has logarithmic slope ~ 2.3 and that the cosmic ray energy density (dominated by $\sim$GeV particles) is $u_{CR} \sim 10^{-12}$erg cm^{-3}. As we know the mean grammage through the galactic disk, $\lambda_d \sim 2$mg cm^{-2} (Cox, this volume), the local flux leaving the galaxy, $\sim \lambda_d u_{CR} c/\lambda_e$ can be computed. Integrating over the disk gives a galactic cosmic ray power of $\sim 3 \times 10^{40}$erg s^{-1}, consistent with an independent determination based on the γ-ray background. This is 3 percent of the fiducial supernova energy (10^{51}erg) times the fiducial supernova rate (30 yr)$^{-1}$. With the possible exception of spiral arms, supernovae are the principal heat source for the interstellar medium. They must therefore be efficient particle accelerators. The elemental and isotopic abundances of cosmic rays, (Simpson, 1983) although differing somewhat from solar composition (especially in the under-abundance of hydrogen) show sufficient similarity to those of solar cosmic rays that it is suspected that in both instances, the particles are injected from a hot ($\sim 10^6$K) coronal gas (Breneman and Stone 1985, Meyer 1985). Electrons are conspicuously underabundant relative to protons (by a factor ~ 30 at the same kinetic energy).

These and other properties of Galactic cosmic rays are broadly consistent with the theory of particle acceleration by the first order Fermi process at a shock front. In this mechanism, the background plasma is idealised as a uniformly moving fluid approaching the shock with speed u_- and leaving it with speed $u_+ = u_-/r$ (in the frame of the shock), where $r = 4$ for a strong shock. The fluid convects elastic scatterers (in practice Alfvén waves) which can scatter high energy particles. Cosmic rays which travel much faster than the shock (with speed v) can cross the shock $\sim v/u$ times. As the scatterers are approaching each other with speed $\sim 3u_-/4$, a typical particle will gain energy by an amount $\sim u/v$ per shock crossing, giving a mean fractional energy increase for the transmitted particles of order unity. As this is a Fermi process, the distribution of particle energies is a power law. However, unlike with most Fermi processes, the slope of this power law is simply fixed by the kinematics. Specifically, we find that the momentum space distribution function, $f(p) \propto p^{\frac{-3r}{r-1}}$. For relativistic particles incident upon a strong shock, the transmitted energy distribution function is $dN(T)/dT \propto p^2 f(p) \propto T^{-2}$. If we allow particles to be freely injected at the shock front and admit some small inefficiency in the acceleration rate, then we see that this proceess naturally accounts for the source spectrum of galactic cosmic rays. If we further notice that protons (and electrons) have smaller Larmor radii at a given energy than heavier nuclei and will therefore be less readily injected into the acceleration mechanism, then we can also account for the observed abundances (Eichler and Hainebach, 1981).

Magnetic Field: Magnetic field is amplified at a plane adiabatic shock. If the angle

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between the shock normal and the field direction ahead of the shock is designated θ_{BN}, then the strength of the post-shock field is given by $B_+ = (\cos^2\theta_{BN} + r^2\sin^2\theta_{BN})^{\frac{1}{2}}B_-$ in terms of the field strength ahead of the shock, B_-. Shocks with $\theta_{BN} \lesssim 45°$ are called "quasi-parallel" and those with $\theta_{BN} \gtrsim 45°$ are "quasi-perpendicular". For a general field orientation and standard interstellar field strength $\sim 4\mu$G, these amplifications are quite inadequate to account for the large field strengths inferred to be present in young supernova remnants. For example in Cas A, a lower bound on the ambient field strength within the remnant of 80μG can be derived from the reported absence of γ-rays (Cowsik and Sarkar, 1980). What seems quite reasonable dynamically (Gull 1973) and is quite consistent with the emissivity distribution (Braun, Gull and Perley, 1987) is that most of the field amplification (i.e., stretching of the field lines) occurs at the interface between the ejecta and the shocked interstellar medium. This makes the outer shock wave rather difficult to locate. In Tycho's supernova remnant, the volume emissivity and hence the implied amplification is much smaller and so the shock is more prominent (Bell, 1979).

In an older remnant like IC443, much of the shocked gas can cool on the expansion timescale and will therefore be crushed by the large post-shock gas pressure. This will in turn accelerate the trapped electrons and compress the magnetic field giving a substantially enhanced volume emissivity from a small fraction of the volume (e.g., Blandford and Cowie 1982).

The polarisation observed from supernova remnants is roughly consistent with these interpretations. In the young remnants, the fields are usually predominantly radial and presumably caused by the strong radial velocity gradients associated with the ejecta. However, in the older remnants, the transverse expansion and the cloud crushing will both tend to accentuate the tangential component of the field as also appears to be generally true. These observations parallel similar trends present in extragalactic jets (e.g., Bridle and Perley, 1984).

Planetary Bow Shocks and Interplanetary Shock Waves: Before dealing in more detail with supernova blast waves, it is instructive to look at collisionless shocks from three differing perspectives. The first is that of a space physicist. The nearest shock is the earth's bow shock which stands off from the earth at $\sim$ 10 earth radii. Conditions in the interplanetary medium ($\rho \sim 10^{-23}$gcm^{-3}, $B \sim 30\mu$G, $u \sim 400$km s^{-1} and $T \sim 10^5$K are similar to those typically associated with supernova remnants when they interact with the interstellar medium. However, there is one respect in which this shock is crucially different from interstellar shocks and this is that its size is quite small, typically 10^{10}cm, only 30 times the Larmor radius of a 10 keV proton whereas a supernova blast wave expands out as far as $\sim$ 30pc. Nevertheless spacecraft observations are able to demonstrate that when the shock is quasi-perpendicular, the actual shock transition, as measured by the thermal ion distribution function or the magnetic field for example, is quite thin—typically a few thermal ion Larmor radii. By contrast, quasi-parallel shocks are quite thick and difficult to localise. A variety of wave modes can be detected in the upstream region, large amplitude low frequency MHD waves, whistlers, Langmuir waves, ion acoustic turbulence, in addition to supra-thermal ion and electron distribution functions. Flybys of the Halley (Sagdeev, *et al.* 1987) and Giacobinni-Zinner comets and the outer planets have detected their bow shocks. As the solar wind is cooler in the outer solar system, the Mach numbers of the shock tend to be larger than at 1AU, (up

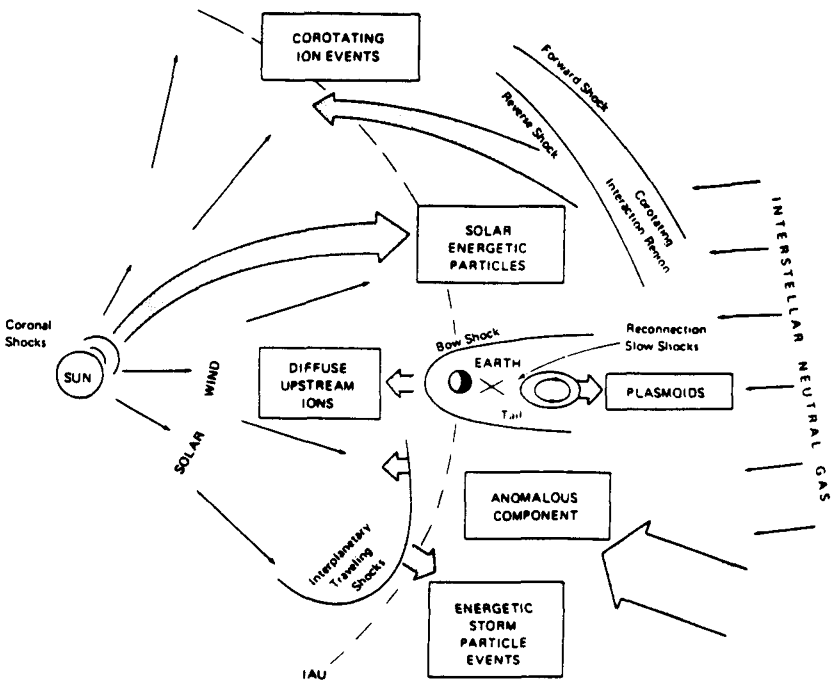

Figure 1. Various particle acceleration sites within the heliosphere (adapted from Scholer 1984).

to $M \sim 20$ in the case of Jupiter).

The travelling interplanetary shock waves, being several AU in radius, are easier to relate to interstellar shocks. Mach numbers in excess of 5 have been reported and again we find that strong quasi-parallel shocks are efficient at accelerating suprathermal protons. The shocks are observed to exhibit several scale lengths associated with the individual components, (Figure 2). A simple but powerful adaptation of the supernova remnant theory of shock Fermi acceleration (Lee 1982) is mostly encouragingly consistent with the detailed observations (*e.g.*Kennel *et al.* 1985). In particular, the relationship between distribution function slope q and shock compression r has been verified, as has deceleration of the background fluid ahead of the shock by backstreaming ions. Unfortunately, interplanetary shock waves are too small to accelerate relativistic particles.

Numerical Simulations of Collisionless Shocks: Another way to try to understand the structure of collisionless shocks is to simulate them on a computer. To date most work has been carried out on perpendicular or nearly perpendicular shocks (e.g., Leroy *et al.* 1982). This is obviously an easier proposition numerically than parallel shocks, because the post shock thermal ions cannot migrate more than a few ion Larmor radii upstream before being convected back into the shock. The magnetic structure seems to be well

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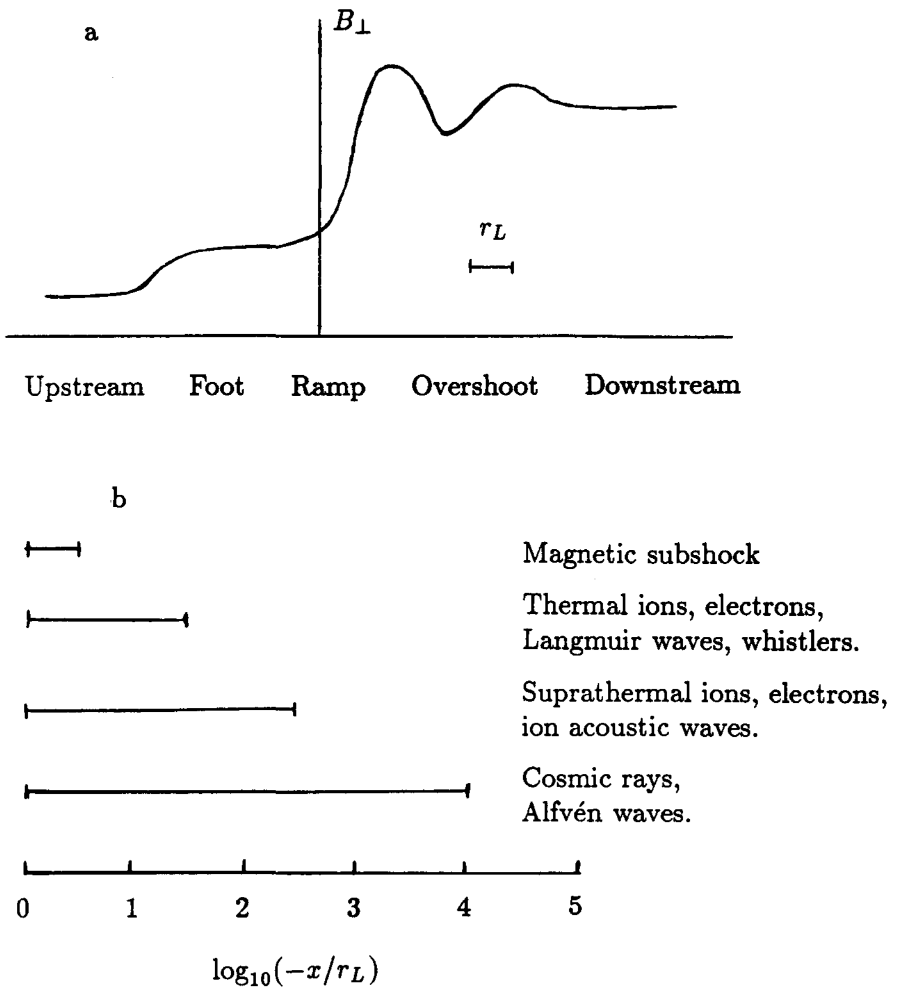

Figure 2. (a) Sketch of magnetic profile of a quasi-perpendicular shock as revealed by spacecraft observations and numerical simulations. The length r_L is the gyro radius of a proton moving with the shock speed in the downstream magnetic field. The thermal ions and electrons are thermalised in a few r_L. (b) Structure of a quasi-parallel shock as inferred from spacecraft observations and theoretical considerations. The scale lengths of the various components ahead of the shock are indicated in units of r_L. Of course, this is only schematic and the details are sensitive to the parameters M, β, θ_{BN}.

established (and is in fair agreement with bow shock observations). Quasi-perpendicular shocks have a precursor "foot" created by the reflected ions. This is followed by a ramp where the field increases rapidly to overshoot its asymptotic downstream value and this is in turn followed by a region in which the field undergoes oscillations about its asymptotic value. The reflected ions have $T_\perp >> T_\parallel$ (with respect to the magnetic field direction.)

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This distribution is unstable and ought to excite lower hybrid waves, especially in the foot. These, and other wave modes can heat the electrons. However, the *downstream* electron temperature is usually lower than the ion temperature.

Rather less work has been carried out on parallel shocks (e.g. Mandt and Tan 1985, Quest 1987 and references therein). Nevertheless, this is broadly consistent with the theory of Fermi acceleration at a shock front. Simulations of this type are restricted to temporal evolution in one space dimension and three velocity dimensions. This may not be too bad an approximation, because the fastest growing wave modes propagate along the magnetic field, although the non-linear coupling of these waves may not be so well modelled. In fact only the ions are followed (together with the electromagnetic fields they generate). The electrons are treated as an adiabatic fluid with charge density equal to that of the ions. This is believed to be a good approximation because the electrons are so light in comparison with the ions. However, in making this simplification, the electrons are expressly forbidden to conduct any heat. Electron heat conduction is observed to be quite significant in the solar wind. Furthermore, electrostatic variations on scales of the plasma period and the Debye length are averaged and assumed not to influence the shock structure.

In the simulations, the ions are fired at a reflecting wall and a stand off shock is allowed to develop (Figure 3). This shock takes several tens of gyro periods to build up and is many Larmor radii in thickness. In the high Mach number ($M \sim 5$) shocks of most interest to us, the incident beam of cold ions is coupled to the post-shock thermal ions by the firehose instability. (The firehose instability is the plasma physics version of the fluid instability that develops when water flows along a sinuous flexible hose and the centrifugal force exceeds the restoring tension in the walls of the hose. It will grow in a plasma when the particle pressure, or more generally the momentum flux along the field exceeds the sum of that across the field and the magnetic tension, $B^2/4\pi$. The firehose instability is non-resonant and essentially all the incoming ions can interact with the magnetic field. Its importance in collisionless shock structure was first recognised by Parker (1961), Kovner (1961), and Kennel and Sagdeev (1967).)

The firehose instability grows so rapidly that in the simulation, the instability criterion is only marginally satisfied. Hydromagnetic waves of non-linear amplitude are sustained just behind the shock and the ions are typically decelerated in ~ 3 Larmor radii. A few ions backscatter ahead of the shock into the undecelerated flow. These suprathermal particles are able to excite Alfvén modes resonantly (as we describe below) and these same waves are carried into the shock by the background fluid because it is moving faster than the Alfvén speed. In addition they are responsible for eventually reversing the motion of the backscattered ions. These ions are the particles that may be injected into the Fermi process. Unfortunately, it is not possible to simulate the entire quasi-parallel shock, because present-day computers still have inadequate speed and memory to encompass all the length scales involved.

<u>Astrophysical Shock Waves</u>: An astrophysicist has yet a third perspective on the general problem of shock structure. As we have emphasised, if cosmic rays are accelerated at supernova shock fronts, then the acceleration has to be pretty efficient. This implies that the cosmic rays are not strictly test particles and may have a strong influence on the shock compression. Furthermore, the simple fact that particles escape the galaxy means

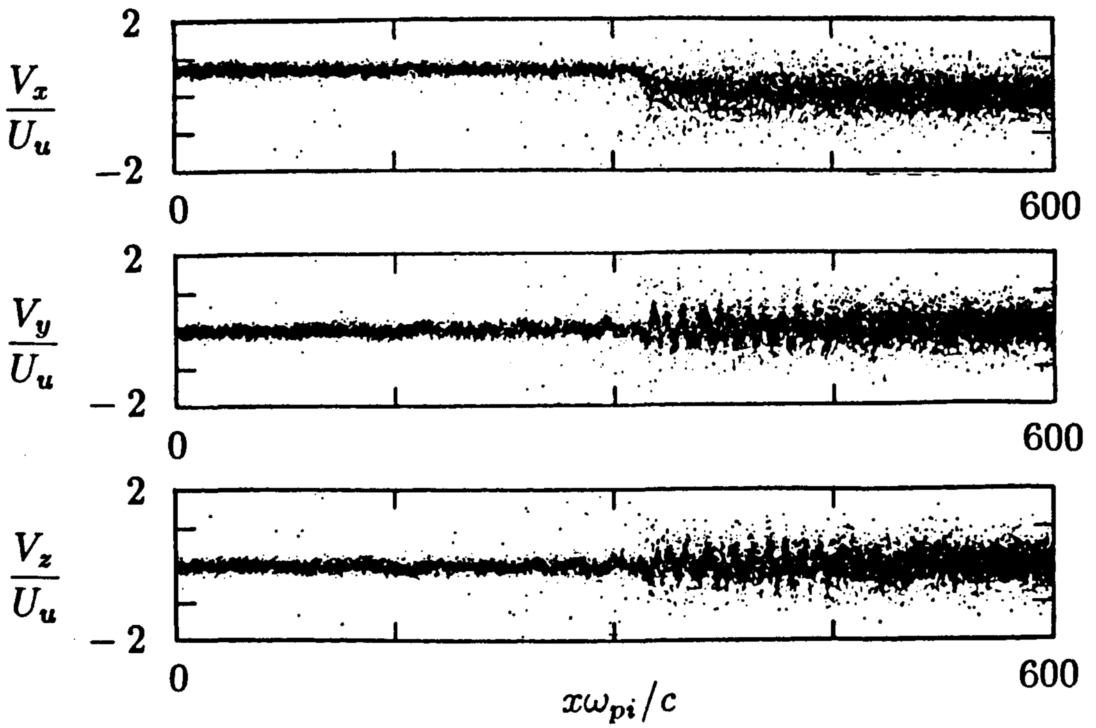

Figure 3. Simulation of a parallel shock by Quest (1987). The shock has an Alfvén Mach number of 5. Distance is measured in units of the ion inertial length (equal to ~ 0.8 thermal ion gyro radii downstream). Note the oscillations in the downstream transverse bulk velocity identifiable as a firehose instability. Also note the backstreaming suprathermal ions ahead of the shock ($V_X > 0$).

that they must be replenished—roughly a thousand times over the age of the galaxy. This process of particle injection, which dictates the abundances in observed cosmic rays, has been a mystery ever since Fermi made his original proposal. There cannot be a pool of subrelativistic though suprathermal particles waiting in the interstellar medium to be overtaken by a shock front and accelerated to GeV energy because they would lose energy so quickly in Coulomb collisions with the ambient plasma that more power would have to be devoted to sustaining this population than would be needed to accelerate the cosmic rays in the first place. Fresh cosmic rays are presumably created at the shock front out of the pool of back streaming suprathermal ions. In this case acceleration can follow immediately after injection so that Coulomb losses are negligible.

These two features of astrophysical shocks were emphasised by Eichler (1979) who also proposed that they might be causally related in the sense that the pressure of the high energy cosmic rays might decelerate the background thermal plasma just enough to control the injection of suprathermal particles. The key point is that the high energy particles should diffuse further ahead of the shock as their gyro radii are proportional to their momenta and so they can act on the incoming fluid before it interacts with the thermal plasma. We can see that high energy particles are possibly important dynamically at strong shocks by observing that the cosmic ray energy density $u_{CR} = \int 4\pi p^2 dp f_+(p)(p^2+m^2c^2)^{\frac{1}{2}} c$ diverges logarithmically as the upper cut off increases when the compression ratio $r = 4$ so that $q = 4$. Furthermore, the net effect of these relativistic particles on the Rankine-Hugoniot conditions is to reduce the effective specific heat ratio of the downstream plasma and therefore to increase the shock compression and to enhance the acceleration efficiency.

This problem of shock mediation by cosmic rays has been addressed in four different ways. Firstly, there have been attempts to finesse it by treating the cosmic rays as a second fluid ignoring its composition, but allowing it to transport heat diffusively (e.g., Drury and Völk, 1981). This probably can only make sense when the dominant cosmic ray pressure is provided by mildly relativistic particles. Solutions for the post-shock conditions can be derived and these may provide a valid description of real shocks, although, as we shall see, they ignore the important effect of Alfvén wave heating of the background plasma. (For a more specific description of the scattering of suprathermal ions involving non-linear Landau damping of oppositely directed Alfvén waves, see Galeev *et al.* 1986). In particular, these solutions demonstrate that it is possible for a shock to exist in which all the entropy generation is associated with the cosmic rays. The background plasma can be simply compressed adiabatically and not pass through an abrupt subshock discontinuity. The relative importance of the cosmic rays is dictated by the choice of their effective specific heat ratio and it is not possible to deduce the efficiency of particle acceleration from a purely fluid treatment (Achterberg *et al.* 1984, Heavens, 1984).

Secondly, Monte Carlo methods have been used (e.g. Ellison and Eichler 1984, Ellison and Möbius 1987). In these computations, an *ad hoc* scattering operator is introduced which is supposed to act on the suprathermal particles as well as the cosmic rays. The reaction of the scattering particles on the pre-shock gas is included self-consistently. What is quite impressive about this approach is that it can provide a good fit to the measured particle spectra for H, He, and C+N+O at the earth's bow shock, which verifies that it is the particle rigidity which effectively controls the composition of the accelerated particles. The form of scattering assumed has little formal justification at present, but the agreement with observations suggest that it is the gyro rather than the Debye length which is important.

Thirdly, kinetic models that solve the convection-diffusion equation for the cosmic ray distribution function $f(p)$ have been computed (e.g., Achterberg 1985, Bell 1987, Falle and Giddings 1987). Here the degree of cosmic ray dominance in the shock is controlled by the low energy source function of the cosmic rays usually parametrised as some small fraction of the incident thermal particle flux. It turns out to be difficult numerically to accommodate a diffusion coefficient that increases with energy as rapidly as expected (roughly linearly). However, the particle spectra are noticeably concave reflecting the larger shock compression and more efficient particle acceleration experienced by the higher energy particles that are able to stream further ahead of the shock.

Finally Eichler (1985) has derived an analytic model of shock mediation incorporating magnetic pressure and wave generation. This approach is able to reproduce the results of Monte Carlo simulations.

So we see with all four approaches, that although the computed shock models may be valid descriptions of real astrophysical shocks, we cannot claim to understand shocks properly until we understand the transport of the suprathermal ions. It is here that the numerical simulations offer great hope, especially if they are successful in reproducing the spacecraft measurements of interplanetary shock waves.

Wave-Particle Interactions: The scattering of high energy particles is believed to be effected by circularly polarised Alfvén waves propagating parallel to the magnetic field. The scattering is resonant with condition

$$\frac{\Omega_g}{\gamma} = k_{\|}v_{\|} - \omega \simeq k_{\|}v_{\|} \tag{1}$$

where Ω_g is the non-relativistic gyro frequency and the subscript $\|$ designates the component resolved along the magnetic field direction. The particle speed is usually much larger than the Alfvén speed $\omega/k_{\|}$, and so the resonance condition is equivalent to requiring that the wavelength be equal to the ion gyro radius. The scattering rate can be simply estimated by observing that each time a particle orbits the field its pitch angle ϕ will change by an amount $(\delta B/B)_{res}$ where res refers to the the resonant field amplitude. These changes in pitch angle are essentially stochastic and so a particle will random walk in ϕ so that its pitch angle will change by of order 1 radian in a time $\sim \nu_c^{-1}$, where the collision frequency ν_C is given by

$$\nu_c \sim \left(\frac{\Omega_g}{\gamma}\right)\left(\frac{\delta B}{B}\right)^2_{res} \tag{2}$$

(One consequence of the relatively small Alfvén speed v_a is that the ratio of the energy change in the particle to the momentum change is $\sim v_A << v$. This implies that the waves are far more efficient at scattering than they are at particle acceleration, which in fact also requires that waves propagating in anti-parallel directions be present.) If we ignore the much discussed but probably illusory difficulty in scattering through 90°, then this is also an estimate of the time for a particle to reverse its direction along the field. We can now estimate the spatial diffusion coefficient

$$D \sim \frac{v^2}{3\nu} \propto \gamma v^2 (B/\delta B)^2 \tag{3}$$

roughly proportional to the particle kinetic energy. This explains why it is generally assumed that higher energy particles stream further ahead of the shock than lower energy particles. In the limiting case, when $\delta B \sim B$ the particles undergo Bohm diffusion, i.e., they random walk of order a gyroradius every gyro period. Numerical simulations by Zachary (1987), verify that large amplitude magnetic fluctuations are created when the cosmic ray density is high and that there is no problem in scattering through 90°.

Long wavelength Alfvén waves must exist in the undisturbed medium where they can inhibit the escape of cosmic rays as we discussed above. However, larger amplitude waves are required and these can be generated by the particles themselves. The linear growth rate can be computed. Imagine that we have an Alfvén wave propagating along the field. Transform into the wave frame where the disturbance is purely magnetostatic.

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Now suppose that resonant cosmic rays (of density n_{CR}) are streaming through this frame in the opposite direction to the background plasma with a mean drift speed v_d. There will be a resonant current density of magnitude $\delta j_{res} \sim n_{CR} e v_d (\delta B/B)_{res}$ and an associated force density acting on the wave of $(\delta F)_{res} \sim (\delta j)_{res}(\delta B)_{res}/c$. This force does no work in the wave frame, but in the plasma frame, it increases the energy of the waves at a rate per unit volume $\sim (\delta F)_{res} v_A$ as long as $v_d > v_A$. The growth rate of the instability is therefore

$$\Gamma \sim \frac{n_{CR} e v_d}{c\rho^{1/2}} \tag{4}$$

We can now use these results to estimate the maximum energy to which a supernova blast wave can accelerate cosmic rays. Two criteria must be satisfied. Firstly, the diffusion length of the particles ahead of the shock must be shorter than the radius of curvature of the shock front, R. This implies that $D/u_- \lesssim R$ or

$$E \lesssim 10^4 (\delta B/B)^2 \mathrm{GeV} \tag{5}$$

Secondly, scattering waves must be able to grow to non-linear amplitude by the time the background plasma has been convected into the shock. Setting $v_d \sim u_-$ the condition $\Gamma^{-1} \lesssim R/u_-$ gives a lower estimate of the maximum particle energy,

$$E \lesssim \left(\frac{u_{CR}(>E)}{10^{-12}\mathrm{ergs}^{-1}}\right)\left(\frac{R}{1pc}\right)\left(\frac{\rho}{10^{-24}\mathrm{gcm}^{-3}}\right)^{-1/2} \sim 10^3 \mathrm{GeV} \tag{6}$$

(e.g., Blandford and Ostriker, 1978; Fedorenko and Fleischman, 1987). In our view, condition (5) is more reliable because quantitative study of interplanetary shocks reveals that the spectrum of hydromagnetic turbulence is not well-described by quasi-linear theory (Kennel *et al.* 1985). Either way, it seems to be very difficult to accelerate protons up to the "knee" in the cosmic ray spectrum at 10^5 GeV.

It is possible that the problem of accelerating to high energy is illusory. The source spectrum can only be inferred directly up to ~ 100 GeV, and if the grammage traversed by the particles λ_e continues to decline up to 10^5 GeV, then the expected particle anisotropy, $\sim \lambda_d/\lambda_e \sim 0.01$ might exceed the observed value. We know that additional components dominate the cosmic ray spectrum at energies $\gtrsim 10^5$ GeV and that there is the possibility that Fe (which can be accelerated by SNR) is also present above 10^4. It seems, to this reviewer, entirely reasonable that supernova shock waves accelerate protons up to 10^4 GeV with non-linear Alfvén waves and that high energy particles are a mixture of heavier nuclei and protons accelerated at larger scale shocks (e.g., a galactic wind termination shock, Jokipii and Morfill 1985).

In fact, conditions for acceleration may be even more stringent than those described because if a shock is efficient at particle acceleration, then the waves must be rapidly damped To see this, it suffices to evaluate the work by the cosmic ray pressure gradient on the Alfvén waves.

$$U_A = \int \frac{dP_{CR}}{dx} v_A \frac{dx}{u_-} = P_{CR}/M_{A-} = \left(\frac{P_{CR}}{\rho_- u_-^2}\right) M_A \left(\frac{B^2}{4\pi}\right) \tag{7}$$

So, if cosmic ray pressure comprises a fraction $\geq M_A^{-1}$ of the total momentum flux, then the waves must be driven non-linear and are probably damped. The energy probably ends up heating the background medium. A critical question to ask of the X-ray observations is: "must the post-shock electron temperature exceed the Rankine-Hugoniot value $(3\mu m_P u_-^2/16k)$ divided by M_A?" If it must, then we can conclude that a subshock is present, and the shock is not totally mediated by cosmic ray pressure.

A somewhat different concern involves the origin of the scattering waves *behind* the shock. Short wavelength hydromagnetic waves are presumably created in abundance by the firehose instability. However, larger wavelength waves, resonant with cosmic rays, may have to be transmitted through the shock. Unfortunately they may be rapidly damped downstream at a general shock with $\theta_{BN} \sim 60°$ because a field parallel mode will be transmitted as an oblique mode subjected to transit time (magnetic Landau) damping. Calculation of the damping rate (Achterberg and Blandford, 1986) suggests that relativistic cosmic rays can be backscattered by transmitted waves but that acceleration of lower energy particles requires wave generation behind the shock.

Electron Acceleration: A topic of more direct interest to the radio astronomers than ion acceleration is electron acceleration. Unfortunately, this is much harder to discuss because it accounts for only a small fraction of the energy available. As is well known, electrons comprise only 3 per cent of the cosmic ray flux at a given kinetic energy. In fact it is one of the ironies of the subject that supernova remnants, which appeared historically to be such spectacularly powerful emitters, are actually quite under-luminous. Cas A radiates roughly 10^{-4} times the maximal synchrotron power of a source of the same energy density. Extragalactic radio sources are often supposed to be radiating the maximum power for their pressure.

It is not hard to understand why shock acceleration should be prejudiced against electrons. The electron gyro radius is smaller than that of a proton of similar energy by a factor ~ 0.02. It is therefore much more difficult to inject electrons into the Fermi mechanism. Indeed, some authors have proposed that electrons are accelerated by a quite separate mechanism. For example, the back streaming reflected ions are able to radiate lower hybrid waves which will be preferentially Landau damped by hot electrons which can in turn be accelerated to relativistic energy (e.g. Galeev *et al.* 1987). Alternatively, the weaker shocks that must surely be present in supernova remnants, can be responsible for second order Fermi acceleration. A third, and quite popular possibility is that a spectrum of hydromagnetic waves be established in the remnant and that this be damped resonantly by the relativistic particles. However, all of these alternative mechanisms require some fine tuning of the effective acceleration and escape times in order to account for the relatively narrow range of observed electron synchrotron radiation spectral indices.

By contrast, suprathermal electrons are produced copiously at interplanetary shocks and even if we are a long off accounting quantitatively for their density, it is surely simplest to imagine that similar electron ejection occurs at supernova blast waves.

A quite different problem associated with electron acceleration is posed by the plerionic remnants like the Crab Nebula. In this case, a central pulsar is believed to lose its rotational kinetic energy through a relativistic electron-positron wind. This wind will shock at a radius where its momentum flux becomes comparable with the ambient remnant pressure. The shock will be relativistic, and so the mean post shock energy per particle will also be relativistic. Plerions are generally observed to have flat radio

https://doi.org/10.1017/S025292110010257X Published online by Cambridge University Press

spectral indices and this could be a signature of a relativistic shock. Indeed, it is possible to account for the IR to γ-ray spectrum from the Crab Nebula by assuming that a power law distribution of positrons and electrons is accelerated with the same mean energy per particle as in the pulsar wind (Kennel and Coroniti, 1984). However, we must ask if the post-shock distribution should be a power law created by the sort of Fermi process we have discussed for non-relativistic shocks. So far most attention has been devoted to the theoretical problem of Fermi acceleration at a mildly relativisitic shock. It is somewhat discouraging that Monte Carlo computations by Kirk and Schneider (1987) indicate that the transmitted particle spectrum steepens as the particle energy is increased.

Observations of electron synchrotron radiation are also very important because they can locate the shock wave and thence constrain the dynamics of the expanding remnant. However, even here there are many puzzles. In the case of Tycho's remnant and that of SN 1006AD (Reynolds, this volume), bright circumferential arcs are seen which are believed to be the shock wave seen tangentially. If the external medium is uniform and its mean compression after being passed by the shock is $4k, (k \sim 2)$ then the shell of shocked gas should occupy a fraction $\gtrsim 1/12k$ of the radius. Some arcs seem to be thinner than this. Furthermore, the polarisation is believed to signify a radial field. A resolution of both problems is possible if the freshly accelerated relativistic electrons are observed through their scattering hydrodynamic turbulence at the shock front.

The outer shocks are not seen in the case of Cas A and the Crab Nebula, although composite supernova remnants (Helfand and Becker, 1987) tell us that they may have quite large radii compared with the brightest emitting regions. Radio maps that can limit the volume emissivity behind an outer bow shock are very important for testing theories of particle acceleration.

Acceleration Efficiency at Quasi-perpendicular Shocks: The empirical evidence from the solar system is that supra-thermal particles can propagate freely upstream in quasi-parallel but not quasi-perpendicular shocks, which ought then to be less efficient particle acclerators. An ingenious argument due Edmiston, Kennel and Eichler (1982), (e.g. Galeev *et al.* 1987), assumes that post-shock particles have a Maxwellian distribution with temperature given by the Rankine-Hugoniot conditions and estimates the fraction of these particles that have sufficient energy to escape upstream away from the shock front. This is large in the case of the quasi-parallel shocks and of course, vanishingly small for perpendicular shocks. Injection should therefore be much easier at parallel shocks.

This argument has been turned on its head by Jokipii (1987) who points out that once particles achieve high enough energy to diffuse freely, they will be accelerated more efficiently at perpendicular shocks because the effective diffusion coefficient away from the shock front will be reduced by a factor $\cos^2 \theta_{BN}$. If a random distribution of the angle θ_{BN} is established along the shock front, then it might be possible to increase the maximum energy to which particles are accelerated. If we consider the limiting case of a perpendicular shock, we find that each time a particle encounters the shock, it must cross it $\sim v/u$ times before it is transmitted downstream. However it acquires an order unity increase in energy in the process. (Strictly, the adiabatic invariant $p_\perp^2/B$ is conserved.) A particle being accelerated at a curved shock front can therefore gain energy in steps $O(1)$ when the shock is locally perpendicular, and this allows particles to continue to

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increase their energy until the radius of curvature exceeds a few Larmor radii. This may allow the maximum energy accelerated to rise as high as 10^5GeV. These ideas may also be of relevance to the so-called "barrel" supernova remnants discussed here by Caswell.

Shock Multiplicity: One issue of concern to cosmic ray physicists, which radio observations may elucidate, is the number of shock waves that accelerate a given cosmic ray before it leaves the galaxy. As discussed above, the difference in the primary and secondary cosmic ray spectra already implies that energetic cosmic rays are not continuously accelerated in the interstellar medium. However, low energy particles may interact several times with weak shocks, and there is some evidence from the detailed abundance ratios that this is actually occurring (Blandford and Ostriker 1980, Wandel this volume).

As has been discussed here many times, a supernova remnant is typically highly inhomogeneous and should contain many weak and some strong secondary shocks. It should be possible to use radio astronomical observations of nearby remnants to quantify this. Furthermore the incidence of weak shocks is strongly influenced by the maximum radius to which a remnant can expand before cooling, which again may be determined observationally. An additional complication, highlighted by McCray's talk here (cf. also Pineault, Landecker, and Routledge, 1987) is that many supernovae may explode in superbubbles of tenuous gas and may lead to efficient acceleration from poorly visible shock waves like that presumed to surround the Crab nebula.

Cosmic Ray Radiative Shocks: We are familiar with the idea of a radiative shock. When the gas is sufficiently dense, the post shock flow can radiate away its internal energy on

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that a fraction of this can be converted into non-thermal emission via a cosmic ray precursor. If we take an extreme view then all of the energy flux in the frame of the shock will be converted into sufficiently energetic relativistic particles to escape. The mass flux in the wind is estimated to be $\dot{M}_w \sim 10^{-5}\mathrm{M}_\odot\mathrm{yr}^{-1}$ from the observations of the non-thermal radio source three days after the explosion (Manchester, private communication), the wind speed is presumably $v_w \sim 500\mathrm{km\ s}^{-1}$ and the shock speed is at least $v_s = 30,000\mathrm{km\ s}^{-1}$. The total cosmic ray precursor luminosity would then be

$$L_{CR} \sim \frac{\dot{M}_w v_s^3}{2v_w} \sim 2 \times 10^{41}\mathrm{ergs}^{-1} \tag{8}$$

roughly 7 times the luminosity of the spot (if it radiates isotropically). Avoidance of the Razin effect in the radio source requires that the field strength in the wind exceed $\sim 10^{-2}$ G and this implies that the escape energy is $\sim 3 \times 10^4$GeV, independent of radius.

We must account for the directionality of the emission. If the progenitor star is rotating, then both the mass flux and the magnetic field strength ought to be strongest at the equator. This means that the high energy particles (presumably protons, as electrons will cool rapidly by inverse Compton scattering the supernova light) should escape preferentially along the rotation axes. However, assuming that the streaming velocity is $\sim c/2$, consistent with the location of the spot, then Doppler beaming should enhance one polar jet relative to the other (and may also reduce the overall power requirements somewhat). We would then observe one jet and if most of the dissipation were at the end, as in the powerful extragalactic radio sources, the jet would appear to be a single spot on one side of the supernova (cf. Rees, 1987).

It is more difficult to account for the spectrum. The natural radiation process is synchrotron radiation by relativistic electrons accelerated at the end of the jet in a locally amplified magnetic field; electron energies $\sim$ 30GeV and a field strength $\sim$ 0.1G will suffice. However the absence of radio emission and the reported steepness of the optical spectrum, which is inconsistent with any pure synchrotron model (Phinney, private communication) are severe problems for this model.

Conclusions: The theory of particle acceleration at a shock front seems to be able to account for most of the observed features of galactic cosmic rays either qualitatively or semi-quantitatively. The spectrum, energetics and overall composition have natural and convincing explanations. The major difficulty with the theory is that it is difficult to account for the observed smoothness of the spectrum up to $\sim 10^5$GeV when supernova shock waves find it difficult to accelerate beyond $\sim 10^4$GeV. Spacecraft observations of interplanetary shocks are providing invaluable empirical information on the mechanics of particle transport and wave generation and, in particular, verify that small scale, non-relativistic particle acceleration is actually occurring. Numerical simulations, now that they are starting to address the problems of quasi-parallel shocks, are equally encouraging and seem to verify the conjecture that the incident ions create scattering waves non-resonantly via the firehose instability and that these ions create scattering Alfvén waves upstream which backscatter them and inject them into the acceleration mechanism. The major uncertainty in the theory, and this unfortunately affects our ability to interpret the best diagnostics we have, *i.e.*the radio and X-ray observations, lies in quantifying

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the electron temperature and suprathermal particle injection rate in different types of shock.

What has become clear in recent years is that the problem of collisionless shock structure and the theory of cosmic ray origin can no longer be considered in isolation. What is equally true is that supernova remants occupy a pivotal position between the interplanetary shocks and the far more energetic activity associated with active galactic nuclei and that a reliable understanding of interstellar particle acceleration is a prerequisite to unravelling the mysteries of quasars. It is hoped that future research will emphasise these linkages.

Acknowledgements: I thank D. Eichler, R. Jokipii, S. Phinney, S. Reynolds and especially C. Kennel for advice and helpful suggestions. I acknowledge support by the National Science Foundation under grant AST86-15325.

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