ACCELERATION MECHANISMS, FLARES, MAGNETIC RECONNECTION AND SHOCK WAVES

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INTRODUCTION

Acceleration in astrophysics usually means converting a significant fraction of the energy of some source into particles whose individual kinetic energy greatly exceeds the average temperature of the medium. There are three general classifications of acceleration processes. The first is hydrodynamic, second coherent electromagnetic, and third stochastic electromagnetic processes. We shall discuss each of these briefly in terms of the spectrum of accelerated particles. This can be related to an efficiency by the relationships $N(>E) \propto E^{-\Gamma}$ or an energy efficiency $N(>E) \propto E^{1-\Gamma}$ In astrophysics we frequently emphasize Γ without realizing the constraints this imposes upon the efficiency of the acceleration mechanism. So often the relatively flat spectra result in efficiency requirements that challenge the ingenuity of those who wish to invent acceleration mechanisms.

HYDRODYMANIC ACCELERATION

Hydrodynamic acceleration generally implies shock waves in matter where either the density gradient or the mass fraction of matter through which the shock wave or sound wave passes, decreases with progression of the wave. The progression from a weak disturbance sound wave to a shock wave is important in many stellar applications; e.g. the damping of oscillations in cepheid variables, the ejection of an envelope in a nova explosion, and in the heating and possible ejection of atmospheres. Ono, Skashita, and Ohyama (1961) were the first to consider the progression from sound waves to shock waves in stellar atmospheres. Since the particle velocity in a sound wave cannot exceed that of the thermal velocities of the medium, this acceleration, although significant in some applications, is still limited to numbers less than the thermal velocities of the ambient medium. Shock waves on the other hand can increase in strength to an arbitrary value and in particular from nonrelativistic

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to relativistic energies provided only that the conditions of density gradient and mean free path apply.

If the mass fraction of matter overtaken by the shock wave decreases either due to a density gradient of converging spherical shock wave, the shock wave will increase in strength. Spherically converging shocks in general do not significantly contribute to acceleration in astrophysics with a possible exception of a converging shock igniting carbon in the carbon detonation of a degenerate presupernova core. Since the density gradient must necessarily be opposite to that required for acceleration in this circumstance, only the strongest external perturbations as for example, large amplitude oscillations of the star could cause a spherically converging shock.

SPHERICALLY CONVERGENT SHOCKS

A spherically convergent shock wave in a uniform medium increases in strength as it approaches the origin. The shock velocity can be expressed as a function of radius and material γ. This problem was first solved by Guderley (1942) and recently expanded upon by Fujimoto and Mishkin (1978).
The kinetic energy behind the shock is proportional to $v^2 r^3$; for a gas of $\gamma = 5/3$, $E[N(>E)] \propto v^2 r^3 \propto v^{-4.58}$, or $\Gamma = 3.29$. Thus the spherically convergent shock is relatively inefficient for accelerating matter.

SHOCK AND A DENSITY GRADIENT

A shock wave speeds up in a density gradient dependent upon the mass fraction of external matter or in turn dependent upon the density distribution through which the shock wave passes.

A shock wave increases in strength in a density gradient in the direction of decreasing density. This has been considered in the theories of origin of cosmic rays by Colgate and Johnson (1960) and in numerical calculations by Colgate and White (1966). These solutions were further extended by Grover and Hardy (1966), who also considered geometry effects. For exponential density gradients the shock velocity or fluid velocity behind a shock increases as $v \propto F^{-1/4}$ to $F^{-1/5}$ depending upon the γ of the gas 5/3 or 4/3 respectively and where F is the fraction of mass ahead of the shock. Therefore $\Gamma = 2$ or 2.5 depending upon γ.

In the radially diverging shock waves in a density gradient as one would expect in a star, the flow following behind the shock wave is as important to acceleration as the shock wave itself. In a strong shock wave, energy is divided equally between internal energy and kinetic energy of matter and so naively one would expect that in a subsequent adiabatic expansion of the matter that the kinetic energy of a given parcel of matter would be roughly doubled. Instead, because the sound characteristics extend from a given parcel of matter inwards to matter that is moving more slowly but which has a higher pressure and energy, a given parcel of matter is accelerated significantly beyond the energy it attained from the shock. I know of no way of estimating this quantity accurately, but numerical calculations have shown (Colgate and White 1966) that when the γ of the gas is 4/3 corresponding to the high entropy adiabats of supernova ejection shock waves, that the energy of a parcel of matter is increased by a factor 4. This factor is surprisingly constant so that a simple power law describes the behavior of the shock wave. We found that with $\gamma = 4/3$ that the effective acceleration of the shock wave produces $N\ (>E) \propto E^{-2.5}$.

Perhaps the more interesting application of this form of hydrodynamic acceleration is that associated with relativistic energies (Johnson and McKee 1971, Colgate and Johnson 1960, McKee and Colgate 1973, Colgate, McKee and Blevins 1972). In relativistic shocks, one expresses the energy as a multiple of rest mass $(\Omega - 1)$, where $\Omega = 1/(1 - \beta^2)^{\frac{1}{2}}$. (In relativistic shock waves the increase in energy immediately behind the shock is less dramatic than in nonrelativistic shocks but then, because the energy density behind the shock is also relativistic, the addition of velocities leads to a product of energies so that the final energy of the expanded matter is a power of the shock energy, not just a fixed multiple (× 4) as it is nonrelativistically. These factors are

$$\Omega - 1_{(\text{shock})} = (F/F_0)^{-\alpha}, \quad \alpha = 0.178 \qquad (1)$$

where F is the external mass fraction of a star through which the shock is progressing and F_0 is the point in the star where the nonrelativistic shock wave becomes relativistic. A reasonable value for F_0 in a compact ($R = \cong 2 \times 10^8$ cm) presupernova star is approximately 10^{-6}. Following the shock the fluid expands and the final energy becomes:

$$(\Omega - 1)_{\text{shock expanded}} = (F/F_0)^{-\beta}, \quad \beta = 0.48 \quad .$$

This results in a final value of accelerated matter $(\Omega - 1)_{\text{expanded}} = 16\ F/F_0^{(-0.48)}$ or a $\Gamma = 2.02$. It should be noted that this value of Γ is greater than the one typically associated with cosmic rays, namely, $\Gamma \cong 1.7$ for the high energy part of the cosmic ray spectrum.

We have often suspected that radiation transport in the expanding matter would lead to a modification of this power law corresponding to further acceleration of the smaller mass fractions by energy transported from the larger inner mass fraction during expansion (Noerdlinger 1971). Our first step in analyzing this has been determining the emitted radiation from a supernova shock wave progressing through an envelope of a compact white dwarf, (Colgate and Petschek 1979). The total energy radiated, several × 10^{44} ergs, is only sufficient to effect the smallest mass fractions at ultra relativistic energy.

One of the unusual characteristics of relativistic shock waves, in stellar envelopes is the exceedingly large lepton density of the pairs created by the thermal radiation. In the highly relativistic region just before the shock breaks through the surface, this lepton density can be 10^4 greater than the baryon density. As a consequence, the dynamic friction as well as the radiation opacity are entirely governed by this extreme light particle density and so the transport properties of this pair fluid must be carefully considered in deriving the relations for the propagation, expansion, and radiation from the shock wave. Figure 1 shows a typical run of variables for shocks speeding up in the envelope of a compact presupernova star. The upper energy limit has been determined by the particular conditions at the surface of the star which defines the analog of a mean free path by the dynamic friction of the pair fluid. The upper energy limit is not calculated in this example; presumably it is several orders of magnitude higher due to the expansion of the outer layer of baryon depleted pair fluid that expands with less recombination than corresponds to equilibrium and so presents an enhanced opacity per baryon during acceleration. Similarly, in addition the propagation of the shock wave in the energy density of a dipole magnetic field is not shown and again one can predict several orders of magnitudes additional acceleration (Colgate,1975).

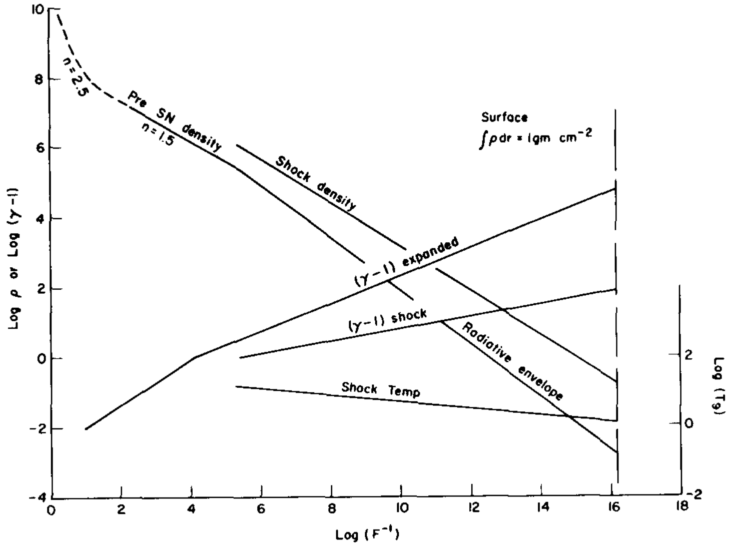

Fig. 1. The presupernova density is shown as a function of mass fraction. The inner core is approximated by a polytrope of index 2.5 and mass 1.5 $M_{\odot}$ with a radiative envelope and radius of 10^8 cm. The energy factor of the fluid velocity immediately behind the shock is shown, as well as the corresponding energy factor after expansion. The temperature in units of 10^9 K of the fluid behind the shock is shown with the scale at the right.

COHERENT ELECTROMAGNETIC ACCELERATION

By coherent electromagnetic acceleration we mean processes where the acceleration force on a particle remains essentially unidirectional during the major period of energy tranfer or acceleration. A classical example of this is a betatron or an electrostatic Van de Graaff accelerator. In laboratory betatrons for engineering reasons the acceleration usually takes place during the rise of the magnetic flux. This is so that the guide field that supports the particle orbit can increase in step with the particle energy. In laboratory plasmas as well as astrophysical circumstances, an othogonal guide field can be supplied and in this case acceleration can take place either during the rising or decaying part of the magnetic flux. In general, however, the interruption of a current leads to more sudden and therefore larger electromagnetic field than occurs for the increasing part of the flux cycle. A classic example of this circumstance in laboratory plasmas is a stabilized pinch where azimuthal magnetic field and axial magnetic field are combined to form a set of helical nested flux surfaces. In the astrophysical context the obvious analog is the solar or stellar magnetic flare or prominence where twisted or helical flux tubes are the generally agreed upon topology of the fields. The topology or description of a twisted helical flux tube is synomous with the equivalent description of an axial current superimposed upon a previously axial magnetic field. In engineering terminology, the interruption of the current along the field that produces the twist gives rise to both a change of inductance as well as change of current so that the voltage becomes $V = d/dt(LI)$ where I is the current and L the inductance. If a particle falls through this potential, then it will end up with a kinetic energy that is some fraction of eV. In toroidal laboratory plasma experiments, this potential can be very large because of the endless nature of the geometry so that a few particles that run away out of the thermal distribution can be accelerated to extreme relativistic velocities.

On the other hand, astrophysical circumstances are in general described by a finite length or arch of magnetic flux terminated on the surface of a star. In this case the maximum total potential is fixed by the current, the time, and length of the flux tube. Up to a point, one can derive these quantities on the basis of first principles, but the major unknown is the time of the interruption of the current. Current interruption, better known as "reconnection" is governed by a hierarchy of nonlinear effects that have yet to achieve a consensus among plasma physicists. (White et al. 1977, Drake and Lee 1977, Yeh 1976, Galeev 1978). However, it is generally agreed that this reconnection cannot take place as fast as, and indeed significantly slower than, the tearing mode (Furth, Killeen and Rosenbluth 1963). One can use the observed quantities for field strength, dimensions, and time, for a large solar flare, say 1000 gauss, a radius of 10^8 cm and length 2×10^9 cm and time 10^3 sec (100 × the Alvén traversal time) to derive a potential of 2×10^9

volts (Colgate, 1978). An ion or electron that runs away from either a collisional or turbulent dynamic friction can therefore pick up a significant fraction of this potential. If one inquires how one would expect these variables to change for other stellar configurations, one must construct a plausible scenario for the formation of such flux tubes.

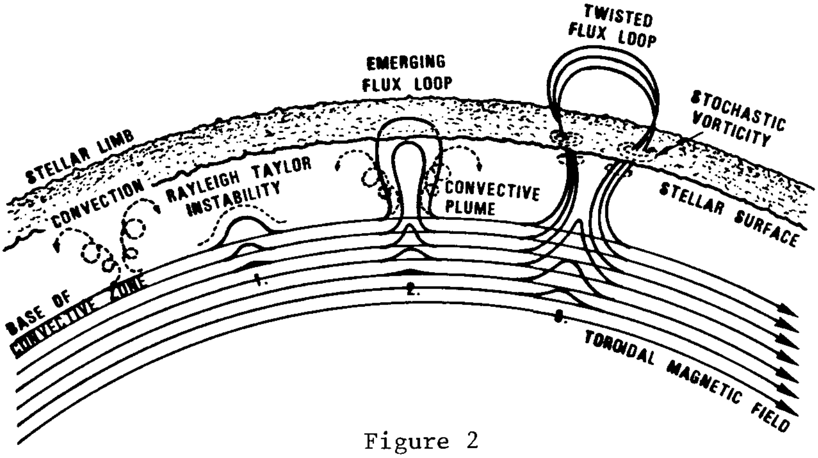

Figure 2

FLUX TUBE ORIGIN

One such model that works surprisingly well for the case of the sun is depicted in Fig. 2. Here the presumed large toroidal field associated with the dynamo in differential rotation (radially differential rotation of the sun) is convected into loops by the primary heat convection of the upper layers of the sun (Fig. 2). The size of the loop is governed by the largest instability length at the onset of convection, namely the scale height at the base of the convection zone. For the sun this is of the order of 2 × 10^9 cm. Secondly, the strength of the magnetic field associated with this loop is limited by the maximum stress (fluid dynamic stress) that the buoyancy associated with convection can exert upon the frozen in magnetic field. One notes that in this case the material pressure is much greater than the magnetic pressure just as the convected stresses are small compared to thermal pressures. In the case of the sun this limits the maximum field of the convected loop to roughly 10^4 gauss which would appear as roughly half of this at the surface of the sun. This agrees with the maximum fields observed in sun spots of ≅ 5000 gauss. When the loop expands above the surface of the sun in the essentially zero pressure chromosphere, the expansion of the flux tube then gives rise to a still lower field of the order a 1000 gauss in the very largest solar flares. The twist of the flux tube most probably is a stochastic twisting of one eddy relative to another as is demanded by the stochastic nature of turbulent convection. This is a quasi-static or slow process and indeed the observed time scales for the emergence of sun spots of several days to a week agrees with the concept of the traveral of scale height, 2×10^{9}, at a convective velocity of 100 m/sec. Since the pressure of the plasma medium is much greater than the magnetic pressure, this means that the classical instability terms are all reversed in algebraic sign giving rise to inherent magnetic stability. When the flux tube is convected above the surface of the sun in the comparative vacuum of the chromosphere, then these criteria for stability are all reversed in algebraic sign and one expects and observes the dramatic instabilities that we associate with a solar flare.

STELLAR FLARES

When one scales this rather simple picture of fluid convection in the formation of magnetic flux loops to other stars where the convective stresses are very much greater (Colgate 1977), then one can predict the upper limiting size of the stellar flare as might occur in a magnetic white dwarf. Under such a circumstance an extremuum of such a flare might be 10^{36} ergs released in a few 10ths of a second giving rise to a potential and therefore acceleration of particles to 10^{14} eV. These numbers are not inconsistent with the estimates of Mullan (1976) who extrapolated solar flares without benefit of such a convective model for the origin of the flux configurations. Of course it should be recognized that in this simplistic view, the particles would simply be accelerated from one end of the flux tube to the other and be buried in the surface of their respective star and would therefore not be observable as accelerated particles in space.

X-RAYS

The x-ray spectrum of the electrons precipitating on the surface would however be observable but the fluxes involved in the current itself are surprisingly small ($\sim 10^{-6}$ to 10^{-4}) of the those required to produce the hard x rays of typical solar flares. To produce the high energy x rays as well as finding an appropriate violation of a nested flux surface geometry to allow the escape of particles, brings us to the role of turbulence and stochastic processes in plasmas.

SYMMETRIES AND INSTABILITIES

The symmetry violating deformations required for the release of the accelerated particles accelerated by the coherent electric fields are less extreme than the turbulence required for the stochastic acceleration of particles. When the topology breaking symmetries that are observed in the laboratory are invoked to explain the behavior of solar and stellar flares, then the general agreement of such a model with observations is both satisfactory and encouraging

(Colgate 1978). However one should recognize most emphatically that a detailed understanding of the reconnection process leading to the observed relatively sudden interruption of the current either in solar flares, stellar flares, or in the laboratory is still a sequence of nonlinear phenomena that is not satisfactorily described in the scientific literature. Let me point out one rather glaring difficulty with our present analytical picture of reconnection.

RECONNECTION

The original reconnection tearing mode work of Furth, Killeen and Rosenbluth (1963) described the enchanced reconnection of field lines within the plane of observation and the othogonal component perpendicular to the plane is at best described as an ignorable coordinate. All descriptions of reconnection from Petschek, (1964) to present describe energization of the plasma primarily perpendicular to the dominant magnetic field that is ignored in first order. Yet on the other hand, the energy that appears from reconnection, as in the earth's magnito tail or in laboratory toroidal plasmas, appears as particle distributions whose kinetic energy is almost entirely parallel to the local magnetic field. Just how the energy released othogonal to the field in first order then appears primarily as a parallel component to the field is a major unexplained factor. Finally, because of the topology $J_{||}$ (current parallel to the field lines) the energy supplied to the deformation of reconnection must appear from a $J_{||} \cdot E_{||}$. The dicotomy of these simple relationships has yet to be unravelled in plasma physics. Finally, the enhanced resistivity that must be a result of reconnection is believed to be caused by plasma turbulence excited initially as ion sound waves by the relative drift of ions and electrons and perhaps, but not certainly, appearing as Langmuir turbulence. In the following section on stochastic acceleration, we will invoke various levels of turbulence as a primary source function for stochastic acceleration. But we should keep in mind that this turbulence is an end product of a $J_{||}$ and an $E_{||}$ derived from Maxwell's equations of the time dependent topological deformation of the magnetic field configuration.

GALACTIC FLARES

We have implied but not stated that the flare or reconnection in a convected flux tube is a necessary part of the closure of any dynamo mechanism. It is obviously and evidently that part of the dynamo cycle associated with the enhanced dissipation of cyclonically convected magnetic flux (Parker 1966). There would appear to be no other obvious source of such enhanced dissipation of fields as the one that we observed in solar and stellar activity. Hence, it is logical to ask where else in the astrophysical medium that we would expect similar phenomena associated with other dynamos. One natural example that comes to mind is the prediction of a galactic dynamo by Parker (1966) because of the necessary short decay times for trapped magnetic flux due to turbulent convection. If the galaxy is a dynamo, then one can use the same scaling as in Colgate (1977) to predict the available potential for the acceleration of galactic particles. The characteristic flux size is that associated with convection at the surface of galaxy, namely several hundred parsecs and the field strength as given by classical galactic fields of a few micro gauss. The times will be some fraction of the the Alvén wave traversal time. This leads to potentials for the unstable reconnection of galactic flares of only a few hundred GeV and so, although this is adequate for injection into other cosmic ray accelerating mechanisms, it does not seem to be the plausible explanation for the full cosmic ray spectrum.

INTERGALACTIC ACCELERATION

On the other hand, since the matter density is small, accelerated particles do not terminate as they do in the surface of a star. There is therefore the possibility of endless geometry, toroidal acceleration as well as stochastic acceleration flare to flare. In the meta galaxy, distances are very much greater and the fields less by ½ power of dimension so if the Alvén velocity is significantly higher than within the galaxies, then possibly flares in the meta galaxy produced by the twist of flux tubes threading galaxies would lead to particle accelerations two to three orders of magnitude greater than our 2×10^{11} eV limit for galactic flares. This indeed is an impressive number but it does not lead to the single step acceleration of the particles of 10^{19} eV demanded by the flattening of the cosmic ray spectrum at these very extreme energies.

Finally in the category of coherent acceleration we should mention the strong wave acceleration associated with pulsars (Kulsrud et al. 1972). If the electromagnetic wave is strong enough such that a particle reaches relativistic energies within one-half wave length of traversal of the wave, then strong wave acceleration takes place. The strength of the wave must be sufficient such that a particle reaches relativistic energy within ½ cycle by its own $\vec{E} \times \vec{B}$ drift in the wave field. Since pulsar frequencies are small and fields strong, very high energy particles can be created. However, the upper limiting energy is many orders of magnitude below what we observe in cosmic rays and only by invoking pulsar fields 10^3 greater than observed can the spectrum be completed. The acceleration of electrons on the other hand, is highly favored, and this mechanism would seem to be the most likely acceleration mechanism that accounts for the high energy electrons that dominate the Crab. As a remaining caveat, it should be pointed out that the original proposed strong wave acceleration considered electrons and ions independently. Instead a large charge separation is created by the preferential acceleration of electrons. This should increase the acceleration of the ions (Colgate 1975) but in a fashion that is not yet known.

STOCHASTIC ACCELERATION

Stochastic acceleration occurs when particles scatter from random fields. The original and classic description of this phenomenon was by Fermi in the proposed acceleration of cosmic rays by moving clumps of magnetic field in interstellar space. Here the acceleration is second order because scattering centers are both approaching as well as receding. Recently it has been proposed that first order acceleration occurs across a shock front by scattering from centers either side of the shock (Blanford and Ostriker 1978). On the other hand, other entities of stochastic scattering for the acceleration of particles can be invoked. On the small scale is the scattering from Langmuir turbulence proposed as the primary acceleration mechanism for electrons in solar or stellar flares (Hoyng 1977). In the preceding section we mentioned an additional stochastic scattering acceleration from the relatively large coordinated electric field associated with reconnection in galactic or metagalactic tortional fields.

There exists a general ordering of stochastic acceleration mechanisms dependent upon whether the acceleration of the particle is in the direction of the particle motion or orthogonal to the particle motion. In the original suggestion of Fermi, particles scattered from magnetic field centers, and in the recent application of the first order Fermi acceleration to interstellar shock waves the acceleration of the particle is also normal to its direction of motion. The other two stochastic acceleration mechanisms, turbulence and tortional field reconnection, accelerate particles by the E•e electrostatic acceleration.

The electrostatic acceleration in Langmuir turbulence is recently discussed in detail by Hoyng et al. (1976) where the Langmuir waves are generated from ionacoustic turbulence behind shock waves. These suggestions have been advanced before by Pikel'ner and Tsytovich (1975), Hoyng (1975) and Benz (1976) but no qualitative analysis was then available. Hoyng discusses how stochastic scattering from Langmuir turbulence leads to an adequate explanation of the acceleration of electrons in solar flares. In this case the Langmuir turbulence is excited by the ionacoutic turbulence behind shocks by induced bremsstrahlung of plasmons from electrons (Tsytovich et al., 1975). The number of electrons per cubic Debye length times the fractional energy in plasma oscillations can be considered an entity more massive then the single electron by this ratio and hence represents a large effective temperature enhancement of the plasma. (Note that the normal energy density in Langmuir oscillations in a thermal plasma is no more than roughly kT per cubic Debye length. The enhancement in effective temperature of plasma oscillations when the fractional energy content in Langmuir turbulence is large, 10^{-2} to 10^{-3} can be many orders of magnitude greater then the particle energies. The superthermal cooperative behavior of the plasma when highly excited in Langmuir turbulence then appears as massive scattering centers for the acceleration of particles. It is therefore not surprising that an exceeding large acceleration of particles can take place. The biggest difficulty with these theories is the uncertainty in the theory of the origin of the Langmuir turbulence. The mechanism of enhanced bremsstrahlung of plasmons from ion sound waves (Tsytovich, et al. 1975) (Langmuir turbulence) has recently come into question (Vlahos and Papadopoulos 1979) who point out the enhanced damping of Langmuir turbulence in the presence of ion sound as originally discussed by Dawson and Overman (1963). On the other hand, the observation of the generation of Langmuir turbulence behind shocks in the presence of strong ionacoustic turbulence belies these objections (Hamberger et al. 1971; Krall 1974; Chin-Fatt 1974). The generation of strong Langmuir turbulence in the presence of strong ion sound waves is a major problem yet to be unraveled in plasma physics.

ASTROPHYSICAL SHOCKS

The idea that important particle acceleration might occur in the vicinity of a shock front is not new. On the other hand, the recognition that this mechanism may be singly important for the origin of cosmic rays has recently received extensive attention. This mechanism offers one important property rendering it especially attractive for astrophysical applications, namely the transmission of a power law distribution function under quite general assumptions. For a strong shock and a gas with a specific heat ratio of 5/3, the acceleration function gives rise to $\Gamma = 3$. Although this exponent is high for the cosmic ray distribution it is on the low range of that observed for other particle distributions and so other complicating effects will tend to steepen it with better agreement with observation. Acceleration in this case takes place because particles can scatter back and forth across a relatively slower moving shock front seeing on the average, a net convergence of the fluid due to the inherent properties of a shock wave. Thus the particles see a first order Fermi acceleration and hence a very efficient accelerating mechanism. An extensive review of this topic has been recently made at the workshop on Particle Acceleration Mechanisms at LaJolla, by Blanford (1979), Krall (1979) and others. The greatest difficulty in considering the first order Fermi shock acceleration mechanism, is an understanding of the nature of the scattering centers ahead and behind the shock. The properties of these scattering centers determine the number of repetitive traversals that a particle can feasibly or probabilistically make across the shock front and hence the overall efficiency of the acceleration mechanism.

CONCLUSION

We have discussed briefly several mechanisms the acceleration of particles in the astrophysical environment. The supernova shock wave models still depend critically on the presupernova star structure and the assumption of highly compact presupernova models for type I supernovae. The most probable resolution of this uncertainty will be the observation of the gamma ray, x ray and early optical behavior (Colgate and Petschek 1979). The acceleration occurring due to the average dissipation of the fields in reconnection and a resulting E parallel has only been observed in the laboratory and is not yet recognized as a possible major contender for the production of cosmic rays and other accelerated particles in the astrophysical environment. This is because the whole process of reconnection is still a major confrontation in plasma physics. The stochastic processes associated with Langmuir turbulence and Alvén wave turbulence have the significant problem of theoretical and experimental verification of the particular mode spectrum of turbulence invoked.

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