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NON-LINEAR EFFECTS OF SELF GENERATED ALFVÉN WAVES IN OBLIQUE SHOCKS AND COSMIC RAY ACCELERATION EFFICIENCY

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RESUMEN. Se presentan resultados numéricos para un modelo hidrodinámico de cuatro componentes (plasma de fondo, partículas energéticas, ondas de Alfvén autogeneradas y campo magnético) para choques oblicuos.

ABSTRACT. Numerical results of a four component hydrodynamic model (background plasma, energetic particles, self-generated Alfvén waves and magnetic field) for oblique shocks are presented.

Key words: COSMIC RAY-GENERAL — PLASMAS — SHOCK WAVES

I. INTRODUCTION

First order Fermi acceleration has been extensively studied as a plausible mechanism for energetic charged particle (ECP) acceleration at shock waves (e.g. Bell, 1978a,b; Drury and Voelk, 1981; Axford et al., 1982; Drury, 1983; Axford, 1985; Blandford and Eichler, 1987; etc.).

The mechanism works in the vicinity of shock waves, where ECP scattered by magnetic irregularities cross the shock back and forth many times between the upstream and downstream regions.

The kinetic energy of the background plasma is redistributed in the shock between both a thermal and a turbulent component, the latter being dissipated downstream over a much wider region than the shock itself. Energetic particles returning upstream from the downstream region are superalfvenic and consequently excite Alfvén waves via the cosmic-ray streaming instability (Skilling, 1975; Bell, 1978a), generating a turbulent region in front of the shock. Both regions act as scatterers for energetic particles, which are able to cross the shock many times, gaining energy in a secular manner due to the relative motion between the upstream and downstream media.

In the simplest approximation (linear theory or test particle approximation (TPA); e.g. Bell, 1978a), for plane shocks and a monoenergetic initial distribution of the particles, a power law momentum spectrum is obtained, whose spectral index is a function only of the kinematical parameters of the shock. The theory is in reasonable agreement with observational data. Linear theory has also the additional attractive feature that injection of the accelerated spectrum in subsequent shocks also results in a power law momentum spectrum, with lower or equal spectral indices (see Bell, 1978b; Lagage and Cesarsky, 1983).

As the compression ratio tends to 4 (upper limit for a strong shock in an ideal monoatomic non-relativistic gas), however, the energetic particle pressure diverges in the linear theory (Drury, 1983). This indicates the necessity of a non-linear treatment which takes into account the effect of cosmic ray pressure on the background flow transition. This has been done by several authors (e.g. for parallel shocks: Drury and Voelk, 1981; Drury et al., 1982; McKenzie and Voelk, 1982 ; and Axford et al., 1982; and for oblique shocks: Webb, 1983; and Webb et al., 1986) in the context of a hydrodynamical approximation.

The most remarkable result of these non-linear treatments is perhaps the formation of a precursor of smooth adiabatic compression followed (or not followed) by an MHD subshock. For certain upstream conditions, there is the possibility of (at most 3) multiple solutions.

As the waves are the link between the background plasma and the accelerated particles, it is important to establish quantitatively the role they play not only in the determination of the structure of the transition via the wave pressure gradient and dissipative effects, but also on the acceleration efficiency through amplification, acceleration time scales (via diffusion

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coefficients), and possibly trapping effects (McKenzie and Voelk, 1982; Drury, 1983; McKenzie and Bond, 1983; Lagage and Cesarsky, 1983).

McKenzie and Voelk (1982) have extended the non-linear hydrodynamic theory to include the effects of self-generated Alfvén wave momentum and energy fluxes on the structure of parallel shocks. We study here the case where all components - plasma, magnetic field, ECP and waves - are put on an equal footing. We developed the basic equations of Webb (1983) to obtain a modified shock structure equation.

Compression ratios and acceleration efficiencies are found and the results are compared with those of Webb (1983) and Webb et al. (1986) - without the wave component - for equivalent upstream parameters. Multiple solutions are also found for intermediate Mach numbers in quasi-parallel shocks.

Following also the basic ideas of McKenzie and Voelk (1982) and Voelk et al. (1984) for parallel shocks,the thermodynamical form of the energy equation is integrated for the case of oblique shocks under the assumption of wave amplitude saturation due to non-linear dissipation The corresponding structure equation is calculated, and a lower limit for ECP acceleration is evaluated for different upstream conditions. Significant differences with the non-dissipative case are only found for sufficiently high Mach numbers and quasi-parallel shocks.

II. FRAME

A one-dimensional steady state inviscid model in a cartesian coordinate system OXYZ has been used. All physical magnitudes are assumed independent of y and z coordinates and only z derivatives are considered non-zero.

The shock wave is at rest at the origin (x=0), being plane and infinite in the y and z directions. The background plasma is flowing from $x = -\infty$ (upstream), towards $x = +\infty$ (downstream), with velocity $U = (U_x,0,U_z)$, immersed in a magnetic field $B = (B_x,0,B_z)$ also restricted to the xz plane.

Four coupled components are included: background plasma, energetic particles, Alfvén waves and background oblique magnetic field.

III. PARAMETERS

The two systems of equations (the saturated and the non-saturated one) are defined in the following parametrical bases:

$$(y_A, y_B, M^2_{SO}, M^2_{CO}, M^2_{WO})$$

or: $$(\beta_0, \theta_0, M_0, N_{CO}, N_{WO})$$

where:

$y_A = V^2_{AXO}$: inverse of the square of the Alfvenic Mach number (B_X component).

$y_B = V^2_{AXO}/U^2_{XO}$: inverse of the square of the Alfvenic Mach number (B_Z component).

M_{SO} : acoustic Mach number (x direction - P_{GO})

M_{CO} : acoustic Mach number (x direction - P_{CO})

M_{WO} : acoustic Mach number (x direction - P_{WO})

$\beta_0 = 2\mu P_{GO}/(B^2_{XO}+B^2_{ZO})$

$\theta_0 = \mathrm{arctg}(B_{ZO}/B_{XO})$: obliquity

$M_0^{-2} = M_{SO}^{-2} + M_{CO}^{-2}$

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1990RMxAA..21..629M

$_{CO} = P_{CO}/(P_{CO}+P_{GO})$: Non-thermal fraction of the total pressure of particles far upstream in the unperturbed medium.

$_{WO} = P_{WO}/(P_{WO}+P_{BO})$: Turbulent fraction of the total magnetic pressure far upstream in the unperturbed medium.

n the other hand, the acceleration efficiency of the shock is defined as:

$$= 100\ (F_{CD}-F_{CO})/(F_{KEO}-F_{KED})$$

here:

$_C$: cosmic ray energy flux (F_{CD}: downstream, F_{CO}: unperturbed)

$_{KE}$: kinetic energy flux (F_{KED}: downstream, F_{KEO}: unperturbed)

.e., it is the fraction of the kinetic energy dissipated in the shock structure which is onverted into cosmic ray (or ECP) energy.

Adiabatic indeces $\tau_G=5/3$ and $\tau_C=4/3$ are used throughout.

V. CONCLUSIONS

Some of the most important features obtained from the numerical solution of the ystem of equations deduced are:

) Total compression decreases when waves are included. (The effect is maximum for parallel hocks, and decreases with increasing obliquity, being zero for perpendicular shocks).

) Saturation of the waves increases the compression of the shock.

) Saturation of the wave decreases the acceleration efficiency.

) The acceleration efficiency increases with increasing M_0.

) Multiple solutions are obtained for quasi-parallel shocks in an intermediate range of M_0. (The ngular range is strongly dependent upon the magnitude of the upstream background plasma β_0, xtending up to quasiperpendicular shocks for small enough β_0).

) The transition (for high M_0) between discontinuous and smooth solutions moves towards higher ach numbers when obliquity decreases from 90 to 0 degrees.

) For quasiparallel shocks a minimum efficiency is obtained at a low Mach number, M_{OM}, at the ransition between solutions with and without a subshock. For still lower M_0 the efficiency ncreases and transitions are totally smooth.

) There is an appreciable increase of the acceleration efficiency with increasing obliquity for ow or moderate Mach numbers. For sufficiently large M_0 the efficiency is practically independent f the obliquity.

) A decrease in β_0 implies a strong decrease in the efficiency for all obliquity and M_0, ssociated with the displacement of the multiple solution region towards larger obliquities.

10) The range of multiple solutions is shifted towards higher M_0 compared with the case when ave effects are neglected (c.f. Webb et al., 1986; Drury and Voelk, 1981).

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