SHOCK WAVES PROPAGATION IN THE TURBULENT INTERPLANETARY PLASMA

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Abstract. Effect of turbulence on interplanetary shock waves propagation is considered. It is shown that background turbulence results in the additional shock wave deceleration which may be comparable with the deceleration due to plasma sweeping. The turbulent deceleration is connected with the energy losses due to the strong turbulence amplification behind the moving shock front.

Key words: Interplanetary Plasma – Shock Waves – Turbulence

1. Introduction

Interplanetary shock waves of flare origin are investigated intensively by interplanetary scintillations and in situ methods (Vlasov, 1988; Watanabe and Kakinuma, 1984; Woo, et al., 1985; Watanabe, 1989; Woo and Schwenn, 1991). It is known from these data that the velocity of the shock front V_s decreases with increasing of the distance from the Sun r

$$V_s \propto r^{-\alpha}. \tag{1}$$

Observed values of the power exponent are within the limits $0.25 < \alpha < 1$, the deceleration rate being dependent on the initial value of shock velocity $V_{s,0}$ in such a way that $\alpha \simeq 0.25$ for low speed ($V_{s,0} - u_0 < u_0$, u_0 is the velocity of undisturbed solar wind) and $0.5 < \alpha < 1$ for high speed ($V_{s,0} - u_0 > u_0$) shock waves.

The scaling and numerical solutions considering laminar plasma with density dependence on the radial distance

$$\rho \propto r^{-2}. \tag{2}$$

give the radial dependence of the shock speed

$$V_s \propto r^{-1/2}, \tag{3}$$

which corresponds to conservation of the whole energy behind the shock surface (blast wave) (Parker, 1961; Dryer, 1974; Dryer, et al., 1984). The observed dependence V_s on r in the case of high speed shock waves is as a rule stronger than (3). The aim of this paper is to show that the solar wind plasma turbulence may put considerable contribution in the strong shock waves deceleration.

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2. Waves transformation on shock surface

Below we discuss the simple model, when the turbulence in the regions before and behind the shock surface is of acoustic type. We consider acoustic waves transformation on shock surface. As it follows from the evolutionary conditions the following inequalities are valid

$$\begin{aligned} c_1 &< v_1 = V_s \\ c_2 &> v_2 \, . \end{aligned} \tag{4}$$

where $c_{1,2}$ - acoustic speeds before and behind the shock surface, $v_{1,2}$ - flow speeds in the shock reference frame. The wave frequency ω' in shock reference frame does not change when wave passes through the shock surface. Using also (4) we obtain

$$\omega' = k_1 v_1 \pm c_1\sqrt{k_1^2 + q^2} = k_2 v_2 + c_2\sqrt{k_2^2 + q^2} \, , \tag{5}$$

where $k_{1,2}$ are the wave vector component, normal to the shock surface, and q is the component in the shock surface plane. Transversal vector component q doesn't change on shock surface. Signs $\pm$ are related to wave propagation towards and outwards the shock in rest reference frame. The relation (5) shows that acoustic turbulence behind the shock will be anisotropic, as only outgoing waves can exist after the shock. For strong shock wave longitudinal component k doesn't change considerably in the case of nearly normal incidence ($q \le k_1$):

$$k_2 \simeq k_1 \, . \tag{6}$$

Now let us consider wave amplitude transformation. For the case of normal incidence (Blokhintsev, 1981; Landau and Lifshits, 1986)

$$\begin{aligned} \frac{\delta p_2}{\delta p_1} &\simeq \eta \frac{p_2}{p_1} \\ \eta &\simeq \frac{1}{\gamma + \sqrt{2\gamma(\gamma - 1)}} \, , \end{aligned} \tag{7}$$

where $\delta p_{1,2}$ are the amplitudes of pressure variations, γ - is the ratio of specific heats. Using the relation,

$$W = \frac{\delta p^2}{\rho c^2} \tag{8}$$

for the energy density of turbulence, we find energy transformation coefficient

$$\chi = \frac{W_2}{W_1} = \eta^2 \left[\frac{2\gamma}{\gamma + 1}\right] M_1^2 \, , \tag{9}$$

where M_1 is the Mach number. Assuming $\gamma = 5/3$ we have

$$\chi \simeq 0.1 M_1^2 \, . \tag{10}$$

For strong shock waves $M_1 \gg 3$ and $\chi \gg 1$, that means the considerable amplification of turbulence behind the shock. At the same time the relative level of turbulence

$$\delta_2 = \frac{W_2}{p_2} = \eta^2 \frac{W_1}{p_1} = \eta^2 \delta_1 \ll 1 \, . \tag{11}$$

Consequently, the turbulence behind the shock will be always weak. Nonlinear processes can not provide the fast isotropisation behind the shock surface, and waves carry away the energy from the shock surface to the inner regions of the flow.

The problem of the magnetohydrodynamic waves transformation on a shock surface is very complicated. But for the case of shock wave propogation in the inner region of the interplanetary plasma, $r \leq 0.5$ a.u., we have more simple situation. Background magnetic field is nearly radial in this region. It changes weakly on a shock surface, but gas pressure increases very strongly. Therefore, the Alfven speed v_a decreases, whereas the acoustic speed c strongly increases. Behind the shock surface high pressure approximation can be used,

$$v_{a,2} \ll c_2 \, . \tag{12}$$

In this case the main energy containing component of turbulence is connected with the fast magnetosonic waves propogating with phase velocity nearly equal to c_2. This component interacts weakly with other modes of Alfenic type. Properties of fast magnetosonic turbulence is similar to the properties of an acoustic wave turbulence. For this reason we can use the equation (9) and (11) for estimations, but the coefficients η and χ may be in principle defined more precisely.

3. Turbulent deceleration of the shock wave

The boundary conditions on the moving shock surface $r = R_s$ with the turbulence taking into account have the following form

$$\begin{aligned} \rho_1 v_1 &= \rho_2 v_2 \\ \rho_1 v_1^2 + p_1 + \pi_1 &= \rho_2 v_2^2 + p_2 + \pi_2 \\ \frac{1}{2}\rho_1 v_1^3 + \frac{\gamma}{\gamma-1} p_1 v_1 + H_{t_1} &= \frac{1}{2}\rho_2 v_2^3 + \frac{\gamma}{\gamma-1} p_2 v_2 + H_{t_2} \, , \end{aligned} \tag{13}$$

where $\pi_{1,2}$ are the turbulent momentum fluxes and $H_{t_{1,2}}$ are the turbulent energy fluxes.

The values $\pi_{1,2}$ and $H_{1,2}$ are proportional to the turbulent energy $W_{1,2}$ (Jascues, 1977). The values W_1 and W_2 are connected by the transformation coefficient χ (9), (10), showing that

$$\begin{aligned} &\pi_2 \gg \pi_1 \\ &H_{t_2} \gg H_{t_1} \ . \end{aligned} \tag{14}$$

The source of the turbulence amplification is the shock wave energy.

The difference of turbulent momentum fluxes (Jascues, 1977)

$$\Delta\pi = \pi_2 - \pi_1 \simeq \pi_2 = \frac{\gamma+1}{2} W_2 \tag{15}$$

acts as decelerating force. The difference of turbulent energy fluxes

$$\Delta H_t = H_{t_2} - H_{t_1} \simeq H_{t_2} = \left(\frac{\gamma+3}{2} v_2 + c_2\right) W_2 \tag{16}$$

discribes the shock flow total energy decrease due to the turbulence amplification.

We shall use the perturbation method for the investigation of evolution of shock wave. Neglecting the turbulent terms in (13) for the zero approximation we obtain for the spherical case the known scaling solution (Parker, 1961)

$$\begin{aligned} &\rho = \rho_2 \left(\frac{r}{R_s}\right), \quad V = V_2 \left(\frac{r}{R_s}\right), \quad p = p_2 \left(\frac{r}{R_s}\right)^3 \\ &\rho_2 = \frac{\gamma+1}{\gamma-1}\rho_1, \quad V_2 = \frac{2}{\gamma-1} V_s, \quad p_2 = \frac{2}{\gamma+1}\rho_1 V_s^2 \ , \end{aligned} \tag{17}$$

where $\rho_1 = \rho_1(R_s)$ is background density, R_s is the distance from the center of explosion, V_s the shock front velocity. We adopt initial energy equation in the form

$$\frac{\partial E}{\partial t} + \mathrm{div}\mathbf{H} = 0, \quad r < R_s \tag{18}$$

where

$$E = \frac{1}{2}\rho V^2 + \frac{1}{\gamma-1} p \tag{19}$$

is the gas energy (without the wave energy), $\mathbf{H}$ - gas energy flux. Carrying out the volume intergation of the energy equation with including the energy losses on shock surface we obtain

$$V_s \frac{d}{dR_s}\left(\int_0^{R_s} E r^2 dr\right) = -\Delta H_t' R_s^2 \ , \tag{20}$$

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where $\Delta H_t'$ is defined by (16) in the rest reference frame.

The solution of (18) may be presented in the form

$$V_s = V_{s,0} \left(\frac{R_0}{R_s}\right)^{\frac{1}{2}} \exp\left[-\frac{7}{4}\eta^2 \int_{R_0}^{R_s} \frac{\delta_1(r)}{r} dr\right], \tag{21}$$

where η is transformation coefficient, $V_{s,0}$ is the shock speed at some initial distance $R_s = R_0$, δ_1 is the relative turbulence level before the shock.

This approximate solution takes into account the work against the force $\Delta\pi$ and the energy carrying away from the shock surface by propagating waves.

For the case $\delta_1 = \text{const}$ we have from (19)

$$V_s = V_{s,0} \left(\frac{R_0}{R_s}\right)^{\frac{1}{2}+\frac{7}{4}\eta^2\delta_1}. \tag{22}$$

As it follows from (20), the power law index in shock speed radial dependence is increased by turbulence on the value

$$\frac{7}{4}\eta^2\delta_1 \simeq 0.2\,. \tag{23}$$

Estimation (23) may be defined more exactly after the careful analysis of different wave modes propagation through the moving shock surface and corresponding calculation of transformation coefficient η with background magnetic field taking into account.

4. Conclusion

The above consideration shows that the strong shock waves propagating in the turbulent medium may be decelerated more rapidly than in laminar case. The turbulent deceleration of shock is connected mainly with the turbulence amplification on shock surface. The energy is transfered by waves from the shock surface to inner regions of the flow. Turbulence behind the shock surface is always weak and highly anisotropic.

References

Blokhintsev, D.I.: 1981, *Acoustics of inhomogeneous moving medium. Nauka. Moscow.* **1**, 1.

Dryer, M.: 1974, *Space Sci. Rev.* **15**, 403.

Dryer, M., Wu, S.T., Gislason, G., et al.: 1984, *Astrophys. Space Sci.* **105**, 187.

Jascues, S.A.: 1977, *Astrophys. J.* **215**, 942.

Landau, L.D., and Lifshits, E.M.: 1986, *Hydrodynamics. Nauka. Moscow.* **1**, 1.

Parker, E.N.: 1961, *Astrophys. J.* **133**, 1014.
Vlasov, V.I.: 1988, *Geomagnetizm i aeronomie.* **28**, 1.
Watanabe, T., and Kakinuma, T.: 1984, *Adv. Space Res.* **4**, 331.
Watanabe, T., and Schwenn, R.: 1989, *Space Sci. Rev.* **51**, 147.
Woo, R., Armstrong, J.W., Sheely, N.R., et al.: 1985, *Nature.* **90**, 154.
Woo, R., and Schwenn, R.: 1991, *Geophys. Res.* **96**, 21
227.