CHAPTER 7
ASTROPHYSICAL MHD SHOCKS

The magnetic field has important roles in the variety of astrophysical circumstances. Complex filamentary structures in magnetized stellar wind, shape and shaping planetary nebulae, synchrotron radiation from supernova remnants, molecular clouds, galactic winds, gamma-ray burst, dynamo effect in stars, galaxy clusters as well as other interesting problems all involve magnetic fields (Hartmann [1]; Balick and Afrank [2]). The turbulent course of mass, momentum, and energy from large to small scales is a universal marvel. Improved characterization of turbulence in magnetized plasmas is a focus of current scientific research which would like to provide a better understanding of the role that turbulence plays in a wide variety of environments, including black hole accretion disks, the interstellar medium, the Sun’s corona, planetary magnetospheres, terrestrial fusion devices, as well as stellar and solar winds. Accordingly Portal et al., [3]; Klessen and Burkert [4]; Ostriker et al., [5] because of formation of filamentary structures in numerical simulation and the appearance of numerous filaments in observation (Falgarone et al. [6]) analysis on the procedures of filament formation and evolution have also been pursued by Kawachi and Hanawa [7], Hennbelle [8]. Bazer and Ericson [9] studied the hydromagnetic shocks for astrophysical application.

Whang [10] studied forward-reverse hydromagnetic shock sets in the heliosphere. In the space material science, the existence of MHD fluctuations in the solar wind was observed. When the fluctuations in the solar wind transmits through the bow shock, the high level fluctuation appear in the magneto-sheath. It is in this manner recommended that study of such non-linear problems may be adiabatic also isothermal both. These phenomenon usually occur in stellar climate where turbulence in medium is more often. Numerous more researchers discover that in stanleous energy discharge along a line cylindrical shocks or along point, spherical
shocks may propagate with expanding quality unbounded. The non-dimensional similarly conditions characterize the example of propagation of such movements and hence, it will be a matter of great interest if it is analysed whether the movement of these discontinuities strong or weak really propagate with high energy yields in the problems solar photosphere rocket reentry fission fusion reactions etc.

Parker[11] studied the flow produced in solar wind using similarity method. The solar magnetic fields that wave in some may connected with sun’s rotation imply large scale magnetic fields may appear in a rapidly rotating planet. The rotation of planet in the presence of a magnetic field is controlled by laws of isorotation i.e. field is symmetric about the axes of rotation and each line of force lies wholly on a surface symmetrical about the relativistic magneto-hydrodynamic (MHD) theory of shock waves is being applied to problems of cosmology and relativistic heavy-ion collisions. In the field of cosmology the shock waves are usually collision-less MHD shocks and are thought to be mostly responsible for the acceleration of particles in a variety of astrophysical objects ranging from active galactic nuclei (AGN) to gamma ray bursts (GRB) (known as first-order Fermi acceleration or diffusive shock acceleration). This phenomenon occurs when the charged particles in the plasma associate with the magnetic fields in the shock layers, and are over and over transported forward and backward across the shock and thereby gaining energy. The commonly observed Earth bow shock indicate that the velocity anisotropic distributions (VAD) of the particles play an important role in the shock formation.

The electromagnetic effects may also be significant, one is thus led to study the interaction of radiation and electromagnetic effects such as may arise in the problem of solar photosphere, rocket re-entry fission-fusion reaction and else where magneto hydrodynamics shocks and detonation are of considerable importance in various field. The objective of present work is to explain the internal rotation motion of stars and turbulence in it which is one of basic problems in astrophysics. It is quite evident that gas dynamics plays a major role in future progress in understanding the detonation phenomenon, explosions along a line. Astrophysical geophysical problem and in technological developments for example propagation of shocks in stellar atmosphere propagation of waves and discontinuities in magneto plasma of solar wind, novae and supernovae out burst, generation of gas imaging
shock waves by magnetic compressive to produce high temperature plasma samples in laboratory exploration of detonation.

the purpose of the present project would therefore be investigate for our present knowledge come be of some help in explaining the real situation in solar wind, novae and supernovae outburst and so many other interesting phenomenon. Elliot[12] discussed self similar solutions for spherical blast wave is air using Rossland’s diffusion approximation under the assumption that there is no effect of heat flux at the centre of symmetry. The problem of the solar wind interaction with interstellar medium attracts close attention in the recent years owing to a continuous stream of data obtained by Pioneer, Voyager, and Ulysses spacecrafts from various regions of the helio sphere. Numerical calculations of Washimi & Tanaka [13], Pogorelov & Semenov [14], Linde et al.[15], Pogorelov & Matsuda [16], Ratkiewicz et al. [17], showed the importance of the interstellar magnetization. These authors performed two and three-dimensional calculations of this problem for various angles between the interstellar magnetic field and velocity vectors $B_\infty$ and $V_\infty$. Fahr et al.[18] also studied the influence of this angle on the shape of the heliopause semi analytically in the Newtonian approximation.

Matsuda & Fujimoto [19] were the first who performed numerical modeling in the axis symmetric case with $B_{\infty} \parallel V_{\infty}$ for various values of the magnetic field. Unfortunately, their results suffered from the lack of space resolution and interpretation of some of them were criticized by Baranov & Zaitsev [20]. This mainly concerned the cases with larger values of the interstellar magnetic field. This point still requires proper clarification. Magneto-hydrodynamic (MHD) discontinuities are frequently encountered in various astrophysical and geophysical phenomena. The variety of MHD discontinuities which satisfy the conservation-law boundary conditions of the Hugoniot type (see Kulikovskii & Lyubimov [21]) is wider than that in pure gas dynamics. It is well known that this variety consists of contact, tangential, and Alfvén (rotational) discontinuities and magnetosonic shocks. The peculiarity of the MHD is in the fact that not all entropy-increasing shocks can exist in nature as stationary structures. The condition of the entropy increase is necessary but not sufficient.

The MHD shocks must also be structurally stable, that is, stable with respect to disintegration into the sequence of other (stable) discontinuities. Note that
disintegration of structurally unstable shocks in the ideal non dissipative state occurs instantaneously under action of an infinitesimal perturbation. This is one of the reasons of difficulties a rising in numerical modeling of MHD flows. Numerical viscosity is widely considered as a tool for selection of admissible shocks in gas dynamics. This is no longer valid for MHD. On the contrary, Barmin et al. [20] showed that numerical viscosity, which is much larger than physical in a number of space physics problems, can sometimes slow down the disintegration of inadmissible discontinuous solutions. Since we expect the physical problem to have a unique solution shock plane we can always make the vectors of magnetic field, velocity, and shock normal lie in one plane ahead of the shock.

The above-mentioned equations for the amplitudes of outgoing waves split in MHD into two subsystems, one of them relating the disturbance amplitudes of quantities lying in this plane and of those perpendicular to it (transverse perturbations). Thus, the evolutionary property must be checked separately for plane and transverse disturbances. As a result, some non evolutionary shocks turn out to be unstable only to out-of-plane disturbances. Akhiezer et al.[23] showed that only fast and slow MHD shocks are evolutionary. These shocks propagate with respect to the unperturbed media at rest with the velocity larger than the fast and the slow magnetosonic velocities, respectively. There is a simple rule to determine whether the shock is evolutionary and therefore physically realizable.

The fast MHD shocks are always super-Alfv´enic, that is, the velocity component normal to the shock is larger than the velocity $V_A = \frac{B_n}{2\sqrt{\rho}}$ of the Alfven wave propagation both ahead of the shock and behind it. The slow shocks are sub-Alfv´enic. Nonevolutionary shocks are trans-Alfv´enic. There are certain types among MHD shocks which require a separate study. These are the cases of perpendicular, parallel, and singular shocks. In a perpendicular shock (it is also sometimes called transverse), the magnetic field vector is perpendicular to the shock normal. Perpendicular shocks are always stable.

7.1 SOLAR MAGNETO-HYDRODYNAMICS CONVECTION

The importance of magnetic field to the dynamics of astrophysical plasmas comes from observations of the outer layers of the Sun. Both the presence of sunspots in the
photosphere and the structures such as filaments, prominences, and flares in the solar corona play the key role that the magnetic fields play in shaping the dynamics. Infect the very existence of the hot corona is now interpreted as due to heating by MHD effect. Beautiful images and animations that show magnetic fields in action in the solar corona have been obtained by recent spacecraft missions such as SOHO, TRACE, YOKOH, HINODE and SDO.

The most of the magnetic activity of the Sun is driven by the combination of rotation and turbulent flows in the convection zone. The properties of Magnetohydrodynamics turbulence driven by convection was discussed by Chandrasekhar in [24]. The evolution of the Sun’s magnetic field in a dynamic process has been a challenging problem for many decades. A process to generation of dipole field due to differential rotation was first proposed by Parker[11]. The convective turbulence play a role in shaping sunspots and coronal activity. Both the processes produce sunspots and the large scale magnetic field of the Sun.

7.2 MHD IN ACCRETION DISKS

The next set of astrophysical systems where magnetic fields have been identified is accretion disks. Such accretion disks are ubiquitous, occurring in proto stellar systems close binaries undergoing mass transfer and in active gal active nuclei. The MRI was first identified by Velikhov [25] in a study motivated by a rotating plasma experiment. Chandrasekhar [26] made important contribution showing the instability in differentially rotating stars. However the importance of the MRI to accretion disks was not recognized by any of these authors. The property of an accretion disk is the angular disk is the angular momentum transport mechanism. This mechanism control the rate of accretion, which controls the luminosity, variability and spectrum of the disk. Mass accretion in disks is analogous to nuclear fusion in stars. It is mechanism that powers the entire system.

To define the angular momentum transport and mass accretion rate, the kinetic viscosity in an astrophysical plasma is too small, so that accordingly Shakura and Sunyaev [27] the some form of anomalous viscosity is required. It also suspected that the transport was associated with turbulence in the disk, but accordingly to Rayleigh criterion disk with Keplerian rotation profiles are linearly stable, that is, so long as the specific angular momentum increases outwards. Disks with Keplerian rotation
profiles which contain weak magnetic field (when gas pressure is larger than the magnetic pressure) are linearly unstable to the magnetorotational instability (MRI). The MRI can be identified by calculating the linear dispersion relation for MHD waves in a Keplerian shear flow. The simplest analysis which captures the MRI assumes incompressible axisymmetric perturbation, a purely vertical magnetic field and ideal MHD. Accordingly Balbus and Hawley [28], the resulting dispersion relation is

\[ \omega^4 - \omega^2 \left| k^2 + 2(k \cdot u_A)^2 \right| + (k \cdot u_A)^2 \left[ \left( k \cdot u_A \right)^2 + \frac{d \Omega^2}{d \ln r} \right] = 0, \]

(7.1)

Where \( u_A \) is Alfvén speed and epicyclic frequency.

\[ k^2 = \frac{d \left( R^4 \Omega^2 \right)}{R^3 dR}, \]

(7.2)

\( R \) is the cylindrical radius. In equation (7.1), the coefficient of first term and the second terms are positive and negative respectively, therefore solutions with \( \omega^2 < 0 \) are possible if the third term is negative. This is possible when

\[ (k \cdot u_A)^2 < - \frac{d \Omega^2}{d \ln r} \]

(7.3)

This defines that if the rotation frequency in the disk decreasing outward (for Keplerian flows), then there are always sufficient small wave numbers that will be unstable. This is in direct contradiction to Rayleigh criterion which requires the angular momentum (not frequency) decrease outward for instability. Size for instability depends on the magnetic field strength \( u_A \). If the field is weak \( (u_A < C) \), there always are unstable modes with wave numbers large enough that the corresponding wavelength is less than the vertical thickness of disk.

### 7.3 MHD TURBULENCE IN THE ISM OF GALAXIES

The next system in which magnetic fields have been observed is the interstellar (ISM) of galaxies. The observation of polarized synchrotron emission from the ISM of the Milky way and other galaxies produced by relativistic electrons spiralling around magnetic field lines, is direct proof of the presence of such field. The observation allow the strength and even the direction of the field to be inferred. In many cases, it
is found the fields are in equipartition with the magnetic energy density being about equal to the thermal energy of the gas and kinetic energy of relativistic particles. Moreover, the observations of the kinematics of the ISM is highly turbulent in galaxies. Thus, the interpretation of the dynamics of the ISM requires an understanding of highly compressible MHD turbulence. One method to investigate the properties of MHD turbulence is direct numerical simulation. Accordingly Lamaster and Stone [29], MHD turbulence is driven with a forcing function whose spatial power spectrum is highly peaked at a wave number corresponding to about 1/8 the size of the computational domain. The energy input rate of the driving is kept constant and the turbulence is driven so that Mach number of RMS velocity fluctuations $M = \frac{\sigma_v}{C}$ is about 7. Where $C$ is the sound speed. The magnetic field strength corresponds to a ratio of gas to magnetic pressure $\beta = \frac{8\pi P}{B^2}$ of 0.01 in the strong field case and 1 in the weak field case. This means the Alfvénic Mach number of the turbulence is about one in the strong field and seven in the weak field. In the weak field case, the density fluctuation are isotropic and the magnetic field is highly tangled. In the strong field case, the density fluctuation are along the field lines and the field is more or less ordered. So that the power spectrum of the turbulence will be anisotropic. Accordingly Goldrich and Sridhar [30], this is one of the most basic predictions of the theory. Most of dissipation was found to occur in shocks. Thus Alfvén waves are important to energetic, the coupling of large amplitude nonlinear Alfvén waves to compressible modes. In particular slow magnetosonic waves cannot be ignored. This coupling pumps energy into the compressible modes decay in shocks. The result shows important implications for the decay of supersonic turbulence in the ISM of galaxies. The comparison between the simulations and observations is possible using the properties such as the polarization angle of background star light. In many regions of the ISM, spinning dust grains with their long axis perpendicular to the magnetic field become aligned. When background stars are viewed through these aligned grains, their light is polarized with the strength and direction of the polarization vector related to the column density of gas and the magnetic field strength in the plane of sky.
Using numerical simulations of MHD turbulence, it is possible to compute theoretical maps of the polarization vectors along different viewing angles. In case of strong fields, the scatter in polarization angle is small. While in case of weak fields the scatter is large. Chandrasekhar and Femi [31] showed that the scatter in the polarization angle \( \delta \phi \) should be related to the plane of sky magnetic field strength \( B_p \), line of sight velocity dispersion \( \delta v \) through

\[
B_p = \frac{0.5 (4\pi \rho)^{1/2} \delta v}{\delta \phi}
\]  

This equation (7.4) is known as the ‘Chandrasekhar – Femi formula’ and used as a technique to measure magnetic field strength in the ISM.

### 7.4 KINETIC MHD EFFECTS IN CLUSTERS OF GALAXIES

In comparison to highly collision plasmas, the most important property of weakly collisional plasmas in the kinetic MHD regime, is that the microscopic transport coefficient become anisotropic. We consider the effect of magnetic fields on the largest structures in the universe, cluster of galaxies. Radio observations of Faraday rotation indicate that x-ray emitting plasma trapped in the gravitational potential of clusters is magnetized. To determine the temperature and density of plasma using the x-ray spectra shows that the mean free path of charged particles in the plasma is smaller than the system size but larger than the plasma in the kinetic MHD regime (gyro radius). If the electron mean free path is larger than the electron gyroradius, thermal conduction is primarily along magnetic field lines. Similarly, if the ion mean path is larger than the ion gyro radius, kinematic viscosity is primarily along magnetic field lines. The description of the dynamics is given by equations of MHD. The addition of anisotropic transport qualitatively changes the dynamics of the plasma. Accordingly Balbus [28], the convective stability criterion with anisotropic thermal conduction depends on the entropy.

If \( \frac{dT}{dz} < 0 \), the plasma is unstable to convection. Convective instability in this regime has been termed the Magneto-thermal instability (MTI). The other instabilities have been also found in the kinetic MHD regime that is important in clusters and diffuse accretion flows.
Consider a stratified atmosphere in a constant gravitational field. Arrange the vertical profiles of the pressure and density so that the atmosphere is hotter at the bottom than the top and the entropy is constant or increasing upwards. By Schwarzschild criterion, in this case the atmosphere should be stable to convection.

Now consider a weak horizontal magnetic field with anisotropic thermal conduction along field lines. Initially the field lines are parallel to the isotherms so that there is no heat flux in the equilibrium state. Consider the evolution of vertical perturbations. The peaks of the perturbations are at a slightly lower pressure than their equilibrium position. The valleys are at a slightly higher pressure and so contract and heat up. These lead to a temperature gradient and a heat flux $Q$ along the field lines. The result is to increase the entropy at the peak and to decrease the entropy at the valleys. This increases the perturbation, tilt the field line more to the vertical and also increases the temperature gradient along the field lines. Therefore this increases the heat flux and this process runs away as instability. The nonlinear regime of the MTI has been studied using numerical simulations. With non-conducting boundaries at the top and bottom of the domain, the MTI saturates when the temperature profile becomes isothermal. If the top and bottom boundaries are held at fixed temperature then vigorous and sustained convection can be driven. Parrish, Quataert and Sharma [32] define that externally driven turbulence plays in the plasma dynamic along with the MTI and other instabilities in the kinetic regime. If the magnetic field vector is parallel to the shock normal, we have a parallel shock (it is also sometimes called normal). Behaviour of parallel shocks strongly depends on whether the Alfvén velocity in front of them is smaller or larger than the acoustic speed of sound. In the former case, slow MHD shocks do not exist, while fast shocks are evolutionary and admissible for all their intensities if the flow is supersonic ahead of them. In the latter case, on the contrary, slow shocks are admissible for all their intensities if the flow is supersonic and sub-Alfvénic ahead of them, while fast shocks are admissible only in a certain range of parameters ahead of the shock even if they correspond to a super-Alfvénic flow. Singular shocks are those for which the tangential component of magnetic field is equal to zero ahead of (behind) the shock and not zero behind (ahead of) it. Such shocks are called switch-on (switch-off), as the tangential component of the magnetic field vector is switched on (off) at them. Switch-on shocks are always fast while switch-off shocks are always slow, since the tangential component of the
magnetic field always increases through fast and decreases through slow MHD shocks.

7.5 SHOCK WAVE EFFECT IN SOLAR WIND

If we increase the value of the interstellar magnetic field $B_\infty$ with the rest of the interstellar medium quantities being fixed. We have two dimensionless parameters relating the quantities in front of the shock, namely, the Mach number $M_\infty = \frac{V_\infty}{a_\infty}$

Where $a_\infty$ is the acoustic speed of sound and the Alfvén number, $A_\infty = \frac{V_\infty}{a_\infty}$. If $a_\infty > a_{1\infty}$ for $M_\infty > 1$, the forward point of the bow shock corresponds to a fast parallel shock which is always realizable. If we further increase $B_\infty$ sooner or later $a_{1\infty}$ will become larger than $a_\infty$ with $A_\infty > 1$. In this case the parallel shock, though remaining fast, will be still evolutionary until $B_\infty B/I$ acquires the value corresponding to $1 < A_\infty < \left[\frac{(\gamma + 1)M_\infty^2}{2 + (\gamma - 1)M_\infty^2}\right]^{1/2}$ (7.5)

A similar formula can be found in Landau&Lifshitz [33] for a particular case of the specific heat ratio equal to 5/3. For $A1$ from the interval (1), the Alfvén number behind the shock is smaller than 1, thus resulting in a trans-Alfénic shock which is inadmissible. Occasionally, a singular (fast switch on) shock becomes admissible exactly in this range of $A_\infty$ (Lyubarskii & Polovin [34]). On a switch-on shock $B \parallel n$ ahead of the shock but $B$ is not parallel to behind it. That is, a tangential component of the magnetic field must appear at the forward point of the bow shock. On the other hand, this cannot occur due to geometrical reasons, since there are an infinite number of switch-on directions and all of them are equivalent. It could be fairly easily expected that the structure of the flow must be different for the mentioned values of $B/I$ from that in the regular case. The MHD shock behaviour is not only important for interpretation of observational data in heliospheric physics, it must be quite clear to those creating numerical codes for MHD simulations. In contrast to pure gas dynamic problems, numerical solution of which can generally be obtained by direct solution of the discretized Euler system, more complicated physical phenomena, though also
governed by hyperbolic systems, require deeper understanding of all mathematical aspects accompanying them (Kulikovskii et al.[35]).

One of the most recent views on the trans-Alfvénic shock behaviour in a magnetized plasma is given by Markovskii [36]. Discussion of numerical schemes that might facilitate the non evolutionary shock disintegration can be found in the paper of Myong & Roe (1998). The flow pattern originating at the forward point of the bow shock in the non evolutionary interval was discussed by Steinolfson & Hundhausen [37] and Matsuda & Fujimoto [19]. Baranov & Zaitsev [20] showed impossibility of the stationary shock configuration presented in the latter paper but did not explain the reason of the phenomenon. Besides, they failed to obtain the solution in the questionable range of Alfvén numbers. Myasnikov[38] obtained the solution similar to that of Matsuda & Fujimoto[19] which turned out to be weakly non stationary so that final solution could not be established. De Sterk et al.[39] studied the plasma flow around an infinite cylinder and found out a variety of MHD shocks, some of them non evolutionary.

In this paper we are revisiting the shock wave interstellar medium interaction problem and perform high-resolution calculations in the two dimensional axisymmetric and 2.5-dimensional statements. In the latter case we add a small axisymmetric rotational perturbation to the interstellar velocity and magnetic field. As a result, only evolutionary shocks remain in the interaction region. This approach lies in the framework of the approach of Barmin et al. [22] who studied the behaviour of the non evolutionary compound wave under action of rotational perturbations. We generally remain in the framework of the statement adopted by Pogorelov & Semenov [40]. Although, the kinetic treatment of the neutral component of the winds was proved to be essential in the shock wave interstellar medium interaction (Baranov et al.[41]), we consider only the charged component and solve the MHD equations for perfect, ideal, and infinitely conducting plasma. The solar wind is assumed spherically-symmetric. The anomalous cosmic rays and the magnetic field of the Sun are disregarded, since they are not crucial for solution of our particular problem. $B_\infty$ is supposed parallel to $V_\infty$. The following set of determining parameters is used (Baranov& Zaitsev [41]):

\[
\begin{align*}
n_e &= 7 \text{ cm}^{-3} ; \\
v_e &= 450 \text{ km/s} ; \\
M_e &= 10 , \\
n_\infty &= 0.07 \text{ cm}^{-3} ; \\
v_\infty &= 25 \text{ km/s} ; \\
M_\infty &= 2
\end{align*}
\]
Index “e” refers to the shock wave 1AU, that is, to Earth’s distance from the Sun. Index $\infty$ “I” corresponds to the interstellar medium parameters at infinity. Here $n$ and $V$ are the number density and the velocity magnitude, respectively, and $M = \frac{V}{a}$ is the Mach number ($a$ is the acoustic speed of sound). The adiabatic index in the adopted approximation is equal to 5/3. We choose such strength of the magnetic field $B_{\infty}$ for which $A = \sqrt{2}$. The dimensionless magnetic field is

$$B_{\infty} = \frac{B_{\infty}}{V_{\infty}\sqrt{n_{\infty}}} = \frac{2\sqrt{\pi}}{A} = \sqrt{2\pi}$$

(7.6)

This corresponds to $B_{\infty} \approx 2.3\mu\text{Gs}$. Calculations are performed in the half-circular region between $R_{\text{min}} = 24\text{ AU}$ and $R_{\text{max}} = 1000\text{ AU}$. The number of cells is 501 in the radial and 504 in the angular direction. Calculations are performed using the TVD second-order of accuracy version of the Lax–Friedrichs scheme proposed and tested for MHD equations by Pogorelov (see Barmin et al. [22]). The advantage of the scheme is in its extraordinary robustness and computational efficiency, though it is obviously more viscous than methods based on the approximate solution of the MHD Riemann problem (Brio & Wu [42], Zachary & Colella [43], Dai & Woodward [44], Aslan [45], Pogorelov & Semenov [40]).

---

**Fig 7.1**
(General configuration of the lines)

**Fig 7.2**
(Stream lines and magnetic field interaction: density)
The flow parameters are fixed at $R = R_{\text{min}}$, since $M_e > 1$. The interstellar medium parameters are fixed for the same reason at the supersonic and super-Alfvénic inflow, whereas absorbing boundary conditions are applied at the subsonic exit segments of the outer boundary (Pogorelov & Semenov [40]).

### 7.6 Result

In this section we present the numerical results for parameters indicated in the previous section. They are subdivided into two parts. The first one concerns a two-dimensional axisymmetric pattern. In the second part, the pattern remains axisymmetric, though the interstellar medium velocity and magnetic field vectors are allowed to have a rotational component.

In Fig.7.1 we present a general view of the solar wind and interstellar medium interaction for the two-shock model. The picture represents the chart of 19 equidistant isolines of the density logarithm (below the symmetry axis) and of the total pressure logarithm located between the minimum and maximum values. If we compare this figure with the similar charts in Pogorelov & Semenov [40], it becomes clear that by increasing the space resolution and by avoiding transient solutions we obtained qualitatively different shape of the bow shock. It is now concave in the vicinity of the symmetry axis.

In Fig.7.2 we show the streamlines (below the axis) and the magnetic field lines. The prominent in the streamline behaviour is that there exist a region around the symmetry axis where they decline towards it, in contrast with their usual inclination for larger Alfvén numbers (or weaker magnetic fields).
REFERENCE


Physics and Astronomy, vol 3


Pergamon Press, London


Birkhauser Verlag, Basel, 589.


[38] Myasnikov A.V., (1997): Preprint No. 585, Institute for Problems in Mechanics,
Russian Academy of Sciences, Moscow

Birkhauser Verlag, Basel, 195.


No. A5, 9575.


