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THREE DIMENSIONAL EXPLICIT MODEL FOR COMETARY TAIL IONS INTERACTIONS WITH SOLAR WIND

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Abstract

The different interactions between cometary tail and solar wind ions are studied in the present paper based on three-dimensional Lax explicit method. The model used in this research is based on the continuity equations describing the cometary tail-solar wind interactions. Three dimensional system was considered in this paper. Simulation of the physical system was achieved using computer code written using Matlab 7.0. The parameters studied here assumed Halley comet type and include the particle density ρ, the particles velocity v, the magnetic field strength B, dynamic pressure p and internal energy E.

The results of the present research showed that the interaction near the cometary nucleus is mainly affected by the new ions added to the plasma of the solar wind, which increases the average molecular weight and result in many unique characteristics of the cometary tail. These characteristics were explained in the presence of the IMF.

Introduction

The interactions between solar wind particle and cometary ions have been studied progressively since 1951 [3]. Solar wind consists of plasma, which includes a wide variety of ions, free electrons as well as gamma rays, emerged within the Interplanetary Magnetic Field (IMF). Comet tail, on the other hand, consists of heavy ions and free electrons only. The plasma tail of the comet is totally shaped by the flow of solar wind facing the moving comet. Its shape is sensitive to any changes in the solar wind properties (density and temperature) as well as the changes in the IMF, thus comet tail can be used as a probe to study solar wind parameters as well as the structure of the IMF. At one astronomical unit (1 AU), the average speed of the solar wind is around 400 km/s. The solar wind average density at such a distance is approximately 7 protons/cm^3.

Most interesting changes in the comet tail are disconnection events, which are thought to occur during crossing IMF sectors. The role of IMF is thought to be an important factor in shaping the comet tail [4], which described by the Magnetohydrodynamic (MHD) theory [5]. Therefore, MHD theory is used to study the changes in the comet tail and thus gives a proper investigation of solar wind. It was confirmed that ideal MHD model combined with source terms can fully describe the interaction between the solar wind and the comet [6].

Many mathematical models are there as well as theoretical treatments used to study and predict the behavior of the comet tail. This can provide better understanding of the physical properties of the solar wind; hence it reveals the structure of solar wind.

Computer simulation has been used ext-ensively to study the solar wind – cometary tail ions interactions since it is the only fruitful method that could be used with ease. With the availability of data collected from he spacecraft missions, computer simulations have more importance to analyze these data. There have been many simulation attempts that showed many important features of the interaction process.

There are many mathematical models used to describe the simulation of the magneto-hydrodynamic model. The most accurate model proposed so far was the non-iterative, 2nd order accurate in time, implicit model proposed by Beam and Warming [1], developed by Schmidt et al. [7] to include three-dimensions. Yet, it is a complicated model because of its prolonged mathematical approach. Other simple models are there, such as explicit methods.

In the present work, computer simulation was used to study comet tail interaction with the solar wind. The simulation has been made to test the present magnetohydrodynamic model describing the interaction between solar wind particles with the cometary tail. The method were used to achieve the simulation here isthree-dimensional Lax Explicit method.

Comets are small, fragile, irregularly shaped bodies composed mostly of a mixture of water ice, dust, and carbon- and silicon-based compounds. They have highly elliptical orbits that repeatedly bring them very close to the Sun and then swing them into space. Comets have three distinct parts: a nucleus, a coma, and a tail. The solid core is called the nucleus, which develops a coma with one or more tails when a comet sweeps close to the Sun. The coma is the dusty, fuzzy cloud around the nucleus of a comet, and the tail extends from the comet and points away from the Sun. The coma and tails of a comet are transient features, present only when the comet is near the Sun. [8].

Our entire solar system, including comets, formed from the collapse of a giant, diffuse cloud of gas and dust about 4.5 billion years ago. When the cloud started its collapse, it was rotating very slowly. The fast rotation helped ensure that not all of the material fell into the core. Instead, the material in the fast-spinning cloud spread out into a flattened disk. Meanwhile, the temperature in the dense, central core was heating up. The core eventually became so hot that it ignited nuclear fusion, creating the Sun [8].

The disk's outer regions, however, were quite cold. The low temperatures allowed water to freeze onto dust grains, which grew in size to make clumps. Some clumps eventually reached a size of several kilometers in diameter. The clumps then began merging, probably by collisions, and formed the planets. Many theories abound about how these clumps became planets. This topic is at the forefront of scientific research. Whatever the details, large planets were created from the buildup of clumps of matter and gas from the surrounding cloud. But some of this matter did not merge into planets.

Within the last decade, for example, astronomers discovered leftover clumps, called planetesimals, in a region beyond Neptune, although no large planets formed beyond that planet. These bodies form an outer asteroid belt at the edge of the solar system, called the Edgeworth-Kuiper belt, named for the scientists who proposed its existence in the 1950's. Recent calculations show that this asteroid-rich Kuiper belt (as it is now known) is probably the source of most of the short-period comets, such as Halley's comet, which orbits the Sun every 76 years.

Nature of Comets Tails

A comet's tail is its most distinctive feature. As it approaches the Sun it develops an enormous tail of luminous material that extends for millions of kilometers away from the Sun. When far from the Sun, a comet's nucleus is very cold and its material is frozen. Water ice, as well as other compounds such as carbon dioxide and carbon monoxide ice, may be found in the nucleus. This icy nucleus changes radically when a comet approaches the Sun. The intense solar wind from the Sun transforms the solid nucleus directly into a vapor, bypassing the liquid phase. This process is called sublimation. The vapor helps stir things up in the nucleus, forcing the core to form a cloud-like mixture of gas and dust around it, called the coma. There, sunlight and the solar wind interact with the ingredients, creating the tails. The ingredients in the coma determine the types and number of tails. Some comets may appear to have no tails, but they really do. They are simply very faint. Scientists can identify these tails by using special filters that are sensitive to dust or gas emissions. Other comets, like Hale-Bopp, which could be seen from Earth in 1997, have very prominent tails. Although Hale-Bopp's tails could be seen visibly from Earth, scientists using sensitive cameras identified a much more complicated tail structure. One of these images revealed a long, curving dust tail. Other pictures showed dust and gas ion tails. There was even an image of a dust tail and two gas ion tails. The different tails provide scientists with important information about the internal chemistry and structure of a comet's nucleus [10].

There are two types of comet tails: dust and gas ion. A dust tail, which is usually yellow, contains small, solid particles that are about the same size as those found in cigarette smoke. This tail forms because sunlight acts on these small particles, gently pushing them away from the comet's nucleus. Because the pressure from sunlight is relatively weak, the dust particles end up forming a diffuse, curved tail. A gas ion tail, which is usually blue, forms when ultraviolet sunlight rips one or more electrons from gas atoms in the coma making them into ions (a process called ionization). A solar wind then carries these ions straight outward away from the Sun. The resulting tail is straighter and narrower. Both types of tails may extend millions of kilometers into space. As a comet heads away from the Sun, its tail dissipates, its coma disappears, and the matter contained in its nucleus freezes into a rock-like material. Recent observations of the very bright comet Hale-Bopp pinpointed a tail made of sodium (Na), a relative of the gas ion tail. This tail forms when sunlight pushes on sodium atoms released from the nucleus [11].

Composition of Comet

Briefly, a comet consists of a clear nucleus, of ice and rock, surrounded by a cloudy atmosphere called hair or comma. The American astronomer Fred L. Whipple described in 1949 the nucleus of the comets, that contains almost all the mass of the comet, as "dirty a snow ball" composed by a mixture of ice and dust [11]. The radicals, for example CH, NH and OH, come from the breakage of some of stable molecules CH_4 (methane), NH_3 (ammoniac) and H_2O (water), that can remain in the nucleus like ice or like composed more complexes and very cold. Another fact that supports the theory of the snow ball is more that it has been verified, in observed comets, than their orbits are turned aside enough of the anticipated ones by the Newtonian laws. This demonstrates that the gas escape produces jet propulsion that slightly moves the nucleus of a comet outside its trajectory, on the other hand, easy to predict. In addition, the comets of short periods, observed throughout many revolutions, tend to vanish with time as it could be expected of those of the type of propose structure by Whipple. Finally, the existence of comet groups demonstrates that the cometary's nuclei are solid units [12].

Magnetohydrodynamic

If collisionless plasma is immersed in a strong uniform magnetostatic field, the system of plasma and static magnetic field can support low frequency electromagnetic waves whose velo-city of propagation can be many orders of magnitude less than the speed of light in vacuum. These low-frequency low-velocity electro magnetic waves are known "*magneto-hydrodynamic*" or "*hydromagnetic*" waves. The frequency of these electro magnetic waves must be less than the cyclotron frequency of the plasma ions if the waves are to display "*hydromagnetic*" characteristics [10, 11, 12].

There are two types of magnetohydrodynamic waves:

1- those whose time- varying magnetic field is parallel to the static magnetic field,
2- those whose time-varying magnetic field is perpendicular to the static magnetic field.

For both it is assumes that the transverse time-varying magnetic field of the magnetohydrodynamic wave are small compare-ed with the static uniform magnetic field, in which the plasma is immersed. In other words, the magnetohydrodynamic to be small amplitude plane waves.

In general, the magnetic and electric fields must not vary in time or space over the orbit of any particles. In such situation, the time-varying magnetic field must be very small or perturbation in comparison with the static magnetic field and the frequency of the time-varying field must be mush smaller than the cyclotron frequency of any charged particles in the system. Under these conditions the magnetic dipole moment of the charged particles will remain constant, and the current densities due to the various drifts of the magnetic dipole moments will be treated as such.

Magnetohydrodynamic Explicit Model

The plasma flow of the solar wind-comet interaction can be described by the equations of ideal magnetohydrodynamics MHD [13,14].

These are modified by source terms which takes into account the addition of heavy, low and cold cometary ions. The main effect on the flow comes from the term in the continuity equation for the mass density ρ .the conservation laws of mass density, no of particles, pressure, and magnetic field can be written in **one dimension** as follows [13]:

1 Mass density:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho v)=\rho_c \qquad (1)$$

where ρ_c is the density resulting from adding new ions to the plasma. These ions are generating from the cometary nucleus, and is given by,

$$\rho_c = \frac{G\sigma m_c}{4\pi r^2 v_c}\exp\left[-\frac{\sigma r}{v_c}\right] \qquad (2)$$

where G is the gas production rate, σ is the specific ionization rate, r is the distance, v_c is the ions velocity and m_c is their mass.

2 Number of particles:

$$\frac{\partial n_i}{\partial t}+\frac{\partial}{\partial x}(n_i v)=n_{ic} \qquad (3)$$

where n_{ic} is the source term for number of particles which is related to $\dot{\rho}_c$ (equation 2) by $n_{ic}=\rho_c/m_c$.

3 Velocity of flow:

$$\rho\frac{\partial v}{\partial t}+\frac{\partial}{\partial x}(\rho v^2+p_g) = 0 \qquad (4)$$

4 Magnetic field:

$$\frac{\partial B}{\partial t}+\frac{\partial}{\partial x}(vB) = 0 \qquad (5)$$

5 Pressure:

$$\frac{\partial \mathrm{P}}{\partial t}+v\frac{\partial \rho}{\partial x}+\gamma\rho\frac{\partial v}{\partial x} = P_c \qquad (6)$$

where

ρ: is the plasma flow mass density,

n_i: is the number of particles,

ρv^2: is the dynamic pressure.

p_g : is the total plasma pressure which is the sum of magnetic pressure $\frac{B^2}{8\pi}$ and the dynamic pressure p.

$$p_g = p+\frac{B^2}{8\pi} \;.. \qquad (7)$$

P_c: is the pressure source term, which is related to the internal energy source term, ε_c. The internal energy term is $\varepsilon_c=\frac{1}{2}\dot{\rho}_c v_c^2$.

The set of equations (1) to (7) can be written in vector forms as follows. The state vector u, is given by:

$$u=\begin{bmatrix}\rho\\ n_i\\ v\\ B\\ p\end{bmatrix} \;........ \qquad (8)$$

and the flux vector is given by,

$$F_{(u)}=\begin{bmatrix}\rho v\\ \rho v^2+p+\frac{B^2}{8\pi}\\ vB\\ vp(1+\gamma)\end{bmatrix} \qquad (9)$$

Initial and Boundary Values Effect

The computer programs used in the present work have a set of initial and boundary conditions that are required to setup the physical properties of the system. These initial and boundary values determine the starting and ending points of the results but not the behavior of the system. Ideally, these values must chosen depending on the limits of case under study.

These programs were tested for initial and boundary values set similar to those found in the reports of Schmidt-Voigt [13], [14] where these values are given in Table (1).

Table (1)
Initial and boundary conditions of references [13, 14].

Parameter		Initial	Boundary
Mass density (kg)	ρ	1.0000×10^{-21}	0
Particles velocity ($m.s^{-1}$)	v	1	10
Magnetic field (Tesla)	B	44.0×10^{-9}	10×10^{-9}
Internal energy (Joules)	E	0	4.0×10^{-12}

Results and Discussions

The results of three dimensional explicit simulation with source are as shown in Figs. (1) to (10). As in the case of no source, the figures were plotted by changing the x-y mesh grid and fixing the value of the z-axis.

Fig. (1) shows the results of the density for the case of source. From this figure it is seen that the source effect with increasing the z-axis is that the peak decreases as the z-axis increases, where it was ~ 10^{-15} at z=5 and became ~10^{-19} at z=14. This indicates that the number of particles and hence the mass density decreases considerably as the values of the z-axis increases, which is as expected since elevation of the z-axis means more distance from the source (the cometary nucleus).

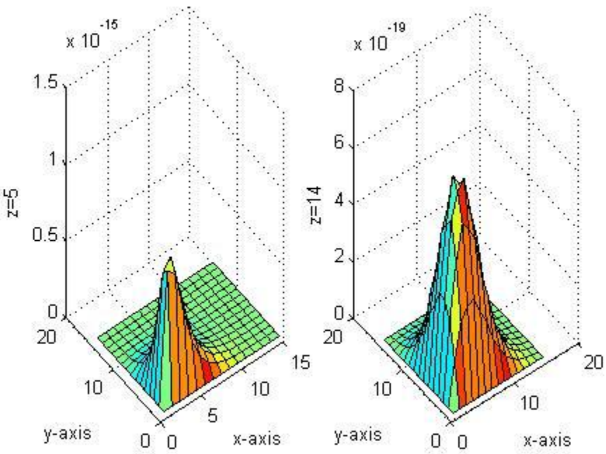

Fig.(1): Relation between particle density for three– dimensional magnetohydrodynamic simulation and space, using Lax explicit method, with source.

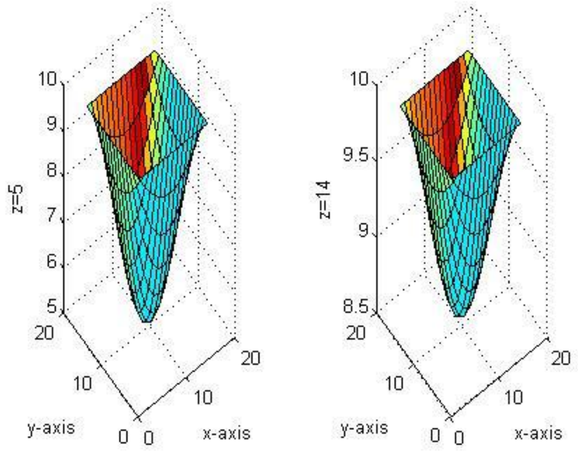

Fig.(2): Relation between velocity V_x for three– dimensional magnetohydrodynamic simulation and space, using Lax explicit method, with source.

Figs. (5), (6) and (7) show the results of the magnetic field components as deduced from the explicit simulation. Since the continuity equation of the magnetic field has no source term, therefore the magnetic field components remain almost the same in this case and the case of source. Similar behavior was reached in all the pervious results of one and two dimensional world simulations.

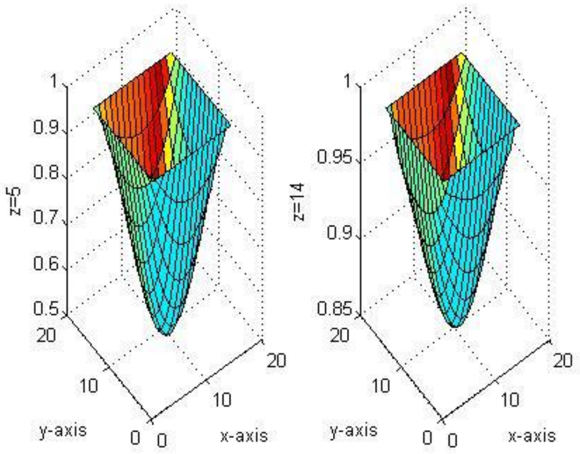

Fig.(3): Relation between velocity V_y for three– dimensional magnetohydrodynamic simulation and space, using Lax explicit method, with source.

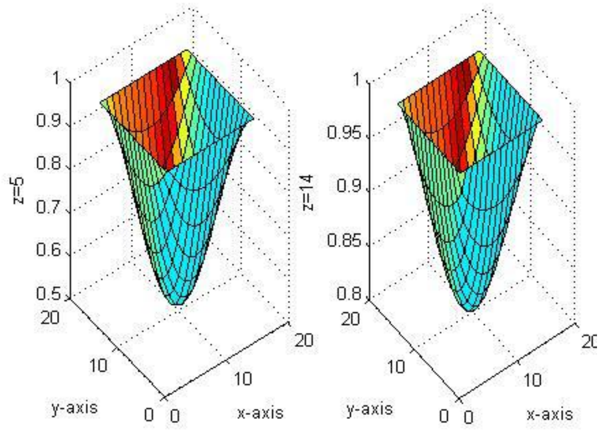

Fig.(4): Relation between velocity V_z for three– dimensional magnetohydrodynamic simulation and space, using Lax explicit method, with source.

The same behavior of the magnetic field components with the velocities is explained as due to the effect of the magnetic pressure [15] where the charged particles of the plasma are confined within the interplanetary magnetic field, and the mobility of these particles is greatly affected by the strength of the magnetic field.

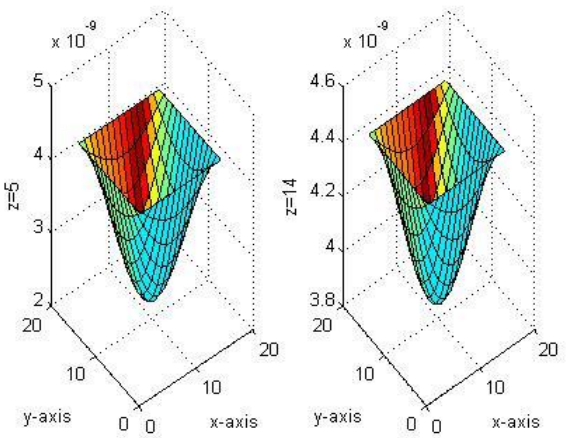

Fig.(5): Relation between magnetic field B_x for three– dimensional magnetohydrodynamic simulation and space, using Lax explicit method, with source.

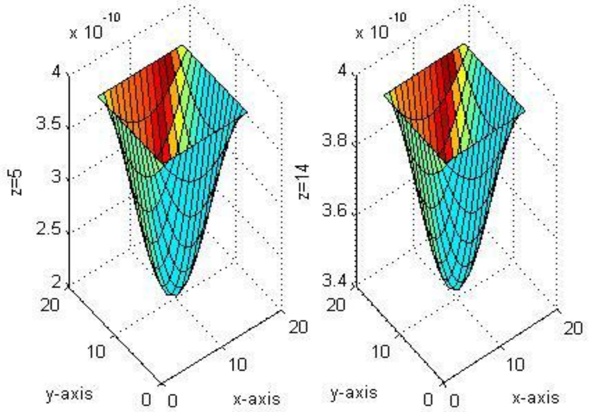

Fig.(6): Relation between magnetic field B_y for three– dimensional magnetohydrodynamic simulation and space, using Lax explicit method, with source.

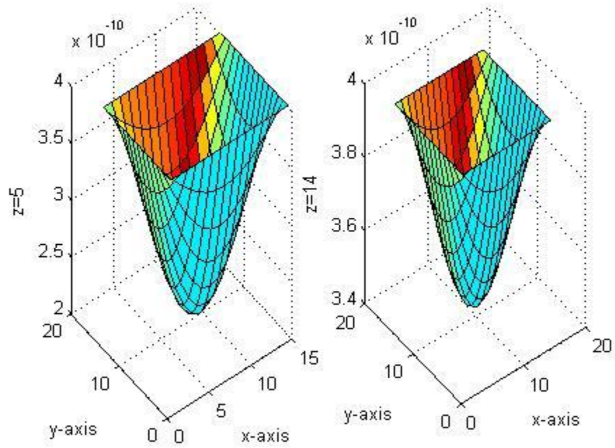

Fig.(7): Relation between magnetic field B_z for three– dimensional magnetohydrodynamic simulation and space, using Lax explicit method, with source.

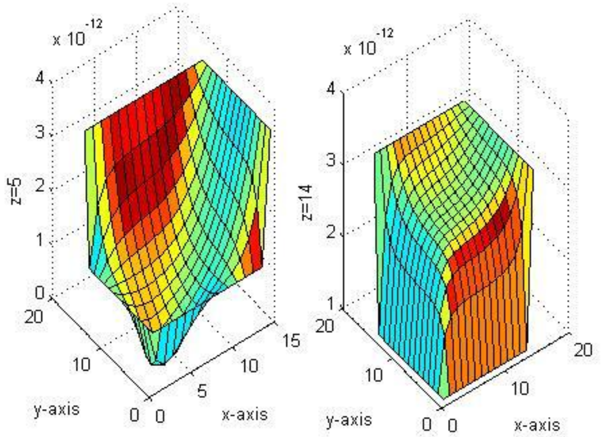

Fig.(8): Relation between pressure for three– dimensional magnetohydrodynamic simulation and space, using Lax explicit method, with source.

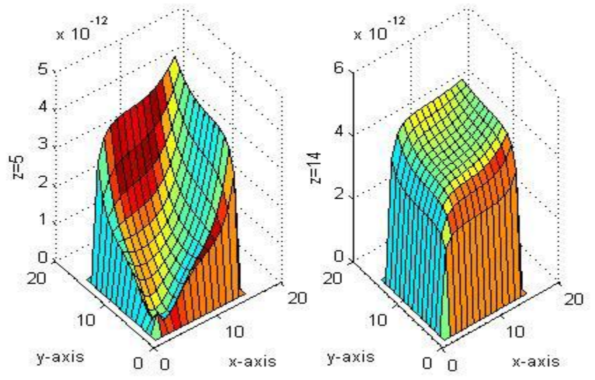

Fig.(9): Relation between energy for three– dimensional magnetohydrodynamic simulation and space, using Lax explicit method, with source.

Figs. (8) and (9) are the results of the pressure and internal energy of the system, respectively. From these figures it is obvious that both parameters increase as the z-axis increases, indicating more effect of the source term in such cases.

Finally, Fig. (10) and (11) show the results of the Alfven wave speed and the speed of sound for the system. Both figures indicate that

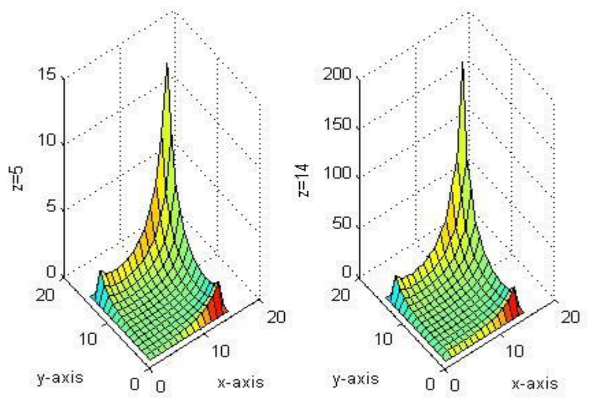

Fig.(10): Relation between Alfven wave speed for three– dimensional magnetohydrodynamic simulation and space, using Lax explicit method, with source.

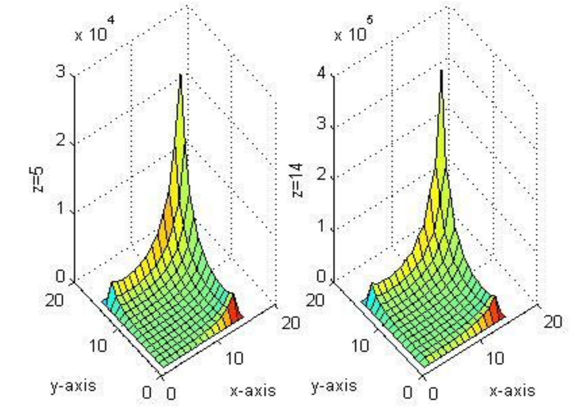

Fig.(11): Relation between speed of sound for three– dimensional magnetohydrodynamic simulation and space, using Lax explicit method, with source.

when source exist, the speed of sound and the magnetohydrodynamic waves increase as increasing the distance from the origin and as the z-axis increases. Similar behavior was found in the case of one - and two-dimensional word simulations.

From these figure it is shown that as the magnetic field decreases with space, the velocity of the particles decreases as well. While as the magnetic field increases the velocity increases. Since the total pressure is composed of magnetic and dynamic pressure, then combining the behavior of these figures with the results of the pressure, Fig. (8, 9), then it is expected that the dynamic pressure plays a minor rule in the system and thus the following fact can be deduced: the dynamic pressure is less than the magnetic pressure. As the magnetic field acts the same as in the case of three dimensional case, then the effects of the dynamic pressure must be less than the effects of the magnetic pressure with a considerable amount.

Conclusions

In the present paper, a numerical simulation of MHD system was made. The system was assumed to reproduce the interactions between cometary tail and the solar wind. Explicit Lax method for three dimensional system was considered.

The results showed that the important specifications of the solar wind can be well interpreted according to the changes of the shape of the cometary tail. From careful study of the mass density variation with space, the conclusion mad here is that the ions destiny reaches the maximum at close distance to the cometary nucleus. This is joined with increment in the number of particles and quite a drop in both of the velocity of particles and IMF magnetic field. Furthermore, the calculations of the total pressure showed that the dynamic pressure plays a minor rule in the system. Therefore it is expected that the dynamic pressure is less than the magnetic pressure.

Reference

[1] Z. Stupar and S. Petrovic, "Computational Fluid Dynamics", University of Belgrade, Mechanical Engineering Faculty, Belgrade, 1996.

[2] Salman Z. Khalaf, "The Effect Of The Solar Wind On The Cometary Tail", PhD. Thesis, University of Baghdad, 2006.

[3] L. Biermann, “Structure of Comets”, Zs. f Astrophys Journal, Vol.29, 1951, pp.274-284.

[4] H. Alfven, “Analysis of MHD for Comet Tail Interactions with Solar Wind”, Tellus Vol. 9, 1957, pp. 92-116.

[5] H. Axford, “Competition of Cometary Nucleus”, Planet Space Sc., Vol.12, 1964, pp. 719-732.

[6] R. Wegmann, "MHD Model Calculations For The Effect Of Interplanetary Shocks On The Plasma Tail of a Comet", Astron. Astrophys ,Vol. 294, 1995, pp.601-613.

[7] M. Schmidt-Voigt, in "Interstellar Magnetic Field", Beck, R., Grave, R., eds., Addison and Sons, Pub, New York, USA, 1987, pp. 251-264.

[8] I. Widad Aref, "Trajectory Analysis of the Cometary Motion and Comets Nucleus Activity", PhD. Thesis, University of Baghdad, 2000.

[9] H. Schmidt and R. Wegmann, "The Comets", available online from http://www.mpa-garching.mpg.de/~ruw/comets.html.

[10] D. E. Osterbrock, "Astrophysics of Gaseous Nebulae", W. H. Freemann and Company Pub., New York, USA, 1974.

[11] L. L. Wilkening, in "Comets", L. L. Wilkening, ed., University of Arizona Press, Tuscon, Arizona, USA, 1982.

[12] B. Buti, "Cometary and Solar Plasma Physics", World Scientific Publishing Company, Singapore, Indonesia, 1988.

[13] M. Schmidt-Voigt, "Time dependent MHD simulation for Cometary Plasmas", Astron. Astrophys., Vol. 210, 1989, pp.433-454.

[14] R. Wegmann, "MHD Model Calculations for the Effect of Interplanetary Shocks on the Plasma Tail of a Comet", Astron Astrophys , Vol.294, 1995, pp. 601-613.

[15] M. R. Voelzke, “Disconnection Events Processes in Cometary Tail”, Earth, Moon and Planets, Vol. 97, 2005, pp.399-409.

الخلاصة

في البحث الحالي تمت دراسة التفاعلات المختلفة بين ايونات الرياح الشمسية وذنب المذنب باستخدام نموذج يعتمد على طريقة لاكس الدقيقة لثلاثة أبعاد. إن الطريقة المستخدمة في هذا البحث تستند على معادلات الاستمرارية للحركة التي تصف ذلك التفاعل. المحاكاة أجريت باستخدام برنامج بلغة الماتلاب لنموذج ثلاثي الأبعاد. العناصر التي حسبت في البحث الحالي تشمل الكثافة الأيونية (□)، سرعة الجسيمات (v)، المجال المغناطيسي (B)، الضغط الحركي (p) والطاقة الداخلية (E).

النتائج المستخلصة من هذا البحث أظهرت أن التأثير الأساسي هو بسبب الأيونات الجديدة المضافة الى بلازما الرياح الشمسية والتي تزيد من معدل الوزن الجزيئي وينتج عنها تغير كبير في خصائص ذيل المذنب. هذه التغيرات قد درست بوجود المجال (IMF).