Three Dimensional MHD Simulation of Comet Hale-Bopp Tail

Salman Zaidan Khalaf [*] ***Ahmed Abdul-Razzaq Selman*****

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Abstract

The interaction between comet Hale-Bopp tail with the solar wind is investigated in the present paper using magneto-hydrodynamic (MHD) numerical simulation, which accounts for the presence of the interplanetary magnetic field (IMF). The simulation is based on three-dimensional Lax-Wendroff explicit scheme, providing second-order accuracy in space and time. The ions produced from the nucleus of the comet will add considerable effects on the microstructure of the solar wind, thus severely altering its physical properties. The present simulation focuses on careful analysis of these properties by means of simulating the behavior of the comet Hale-Bopp's tail at 1 AU from the sun. These properties include the changes of the plasma density, particle velocity, IMF changes, pressure, and internal energy. The results indicated that comet tail will highly disturb the physical properties of the solar wind for a considerable distance. These changes reflect the effect of including the source term in the present simulation. It is shown that the comet tail will retain its original shape faster as it approaches the sun. Practical comparisons are also presented in the present research with earlier work. The present simulation was made using MATLAB program.

1. Introduction

The structure of the cometary nucleus is thought to compose from ice mainly [1]. The so called "*dirty-ice model*" is based on the assumption that the comet nucleus is composed from water ice contaminated by various impurities. This unique structure of the comet nucleus makes it possible to generate the cometary tail and thus provides important tool for studying the solar wind properties.

In the inter-planetary region of the solar system, comets are totally emerged in the solar wind. The cometary nucleus moves in a specific path due to the gravitational force applied on it by the sun. During its path, comet nucleus will suffer from the solar radiation. These energetic radiations from the sun will ionize the atoms and molecules of the ice in the comet nucleus, and produce coma gases. Some of these gases are totally ionized and the interaction of cometary plasma with the magnetized solar wind produces the plasma tail. Mainly, the ions produced from comets are H_2O^+ and CO^+ [2]. These ions are trapped into the magnetic field lines because of their extra charge, which will force many changes in the inter-planetary magnetic field (IMF) properties.

The study of the comet tail with the solar wind is possible by means of the magneto-hydrodynamic (MHD) system. The MHD is basically a macroscopic plasma turbulence that occurs due to electromagnetic phenomena. Therefore, if the changes

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* Department of Astronomy, College of Science, University of Baghdad
** Department of Physics, College of Science, University of Baghdad

of the IMF due to comet presence were studied, then it will be possible to study many entities at the same time, such as: (a) cometary properties, namely, gas production rate and the molecular structure, (b) solar wind properties, including its density and pressure, (c) the structure of the IMF specially in the IMF sector boundaries, and (d) the nature of the interaction between comets and solar wind. Thus, one can see that cometary tail studies provide important source of information concerning solar wind.

In the present paper, a computer simulation is made to study the interaction between the tail of the comet Hale-Bopp with the solar wind and see how the features of the environment will change. The current method is based on the Lax-Wendroff three-dimensional explicit scheme. The focus will be on the solar wind properties changes, namely, particle number and density, their velocity, the turbulence in the IMF, and the magnetic pressure caused by this interaction, the total pressure changes due to comet presence and the internal energy of solar wind particles. Also, these effects are studied according to the position of the comet from the sun.

In Section II, a brief review on the cometary tail interaction with the solar wind is given. Section III is focused on the MHD equations of the system and the details of the numerical method used in the present paper. In section IV, the results are outlined and discussed in details. Finally, the conclusions and suggestions are provided in section V.

2. Comet Tail Interactions With Solar Wind

Hale–Bopp comet is the largest and most productive known comet. It was discovered when it was at a far distance from the sun. These specifications of this comet made it possible to be observed and studied by means of its activity even when it is at a large range of heliocentric distance. There have been many attempts to review the important observations about this specific comet [3, 4, 5] regarding the relations between dust and gas production rates. The plasma tail of the comet possesses many different spatial structures such as rays, knots and disconnection events. The formation and dynamics of these structures are determined mainly from the changes of the properties of the solar wind streaming near by the comet. Therefore, the observation of the ion tail is used to have better understanding of the details of the interaction between comet tail and solar wind. [5]

Ions measurements were performed previously by many spacecraft missions to comets Halley and other comets, and in numerous ground-based observations of cometary ion tails [6, 7]. These observations gave us important thoughts to improve the numerical investigations of the solar wind interaction with all types of comets. Also, the importance of ions addition in this reaction near by and inside the inner coma of the comet are investigated [8, 9], which provides more details about the specifications required in numerical simulations of comets.

Due to its incredibly large size, comet Hale-Bopp (C/1995 O1) was studied extensively in the past years [2, 3, 4, 6, 7, 8], allowing to perform observations ranging from the millimeter wavelength up to the extreme ultraviolet range. Ion density, distribution, velocity and magnetic field disturbances were all derived for this comet by various techniques.

The orbit of Hale-Bopp moves in inclined orbit by 89^o to the ecliptic plane, and following the tail activity along its orbit. This allowed the investigation of the interaction with the solar wind over a wide range of heliospheric latitudes. As a result of its brightness, Hale-Bopp provided a special opportunity to search for ion emissions at a wide range of wavelengths. This resulted in the first detection of CO^+ in this wavelength range and the first observations of H_3O^+ and HCO^+ emissions in comets. Including these new detections, eleven ions have been observed by their emission lines [4] in comets, which are: H_3O^+, H_2O^+, HO^+, CO_2^+, OH^-, CH^+, CO^+, N_2^+, O^+, C^+ and Ca^+. Comet Hale-Bopp is chosen in the present simulation because of these special properties, which make this comet a unique one and worth to study.

3. MHD Model

Plasma flow from the comet tail will cause important interactions with the solar wind plasma. This interactive system can be described by the equations of ideal magnetohydrodynamic equations (MHD), modified by source terms which take into account the addition of heavy ions generated from the cometary nucleus with the solar wind. Mainly, the effect on the plasma flow comes from the term in the continuity equation for the mass density, ρ . This source is the most important one during cometary tail interaction with the solar wind. However, there are other sources that should be pointed out here. These include velocity source and charge source. These sources, however, contribute with less than ~ 2% in the total source terms needed for accurate simulation [6].

A proper numerical solution of the physical system should be found in order to describe the behavior in satisfactory manners. There are many numerical schemes used for comet tail interaction with solar wind [10], of which Lax-Wendroff is chosen in this paper due to its efficiency.

The MHD conservation laws for comet tail include conservation of mass density ρ, number of particles n, pressure p, and magnetic field B, are given as follows [7],

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}.(\rho \vec{v}) = \dot{\rho}_c \tag{1}$$

$$\frac{\partial n_i}{\partial t} + \vec{\nabla}.(n \vec{v}) = \dot{n}_{ic} \tag{2}$$

$$\rho \frac{\partial \vec{v}}{\partial t} + \vec{\nabla}(\rho v^2 + p_g) = 0 \tag{3}$$

$$\frac{\partial \vec{B}}{\partial t} + \vec{\nabla}.(\vec{v} \times \vec{B}) = 0 \tag{4}$$

$$\frac{\partial e}{\partial t} + p\vec{\nabla}.\vec{v} + \vec{\nabla} \cdot (e\vec{v}) = 0 \tag{5}$$

ρ : is the plasma flow mass density,
n_i : is the number of particles,
v : is the particles velocity,
p: is the plasma pressure,
e : is the internal energy.

The above set of equation (1) to (5) can also be written in vector forms in order to make them in a clearer picture, as follows:

$$U = \begin{bmatrix} \rho \\ n_i \\ v \\ B \\ e \end{bmatrix} \qquad (6),$$

where U is the state vector in this case, and the flux vector, F, is given by,

$$F_{(u)} = \begin{bmatrix} \rho v \\ \rho v^2 + p + \dfrac{B^2}{8\pi} \\ vB \\ vp(1+\gamma) \end{bmatrix} \qquad (7).$$

These sets of equations -eq.(1 to 5) or eq.(6 and 7)- are sufficient for the present astronomical model [7].

When the IMF becomes frozen in the flow, it piles-up in front of a diamagnetic cavity which separates the mass-loaded solar wind from the purely cometary plasma. The cometary ions then are quickly accelerated by magnetic curvature and pressure forces to the ion tail [5, 11, 12]. The size of the interaction region of a cometary ionosphere, R_I, with the solar wind is proportional to the ionization rate, σ, the molecular weight, m_C, the gas production rate, G, particle speed, v, and the solar wind flux, $\rho_\Theta U_\Theta$, such as, [7, 8, 11, 13]

$$R_I = \frac{\sigma\, m_C\, G}{4\,\pi\, v\, \rho_\Theta\, U_\Theta} \qquad (8)$$

where ρ_Θ is the original (undisturbed) solar wind density and is the speed of unperturbed particles, respectively.

This indicates that the size of the interaction zone varies with the production rate, G, for a given solar wind set of conditions [7, 8]. As an example, in the comet Hale-Bopp, G is about $1\text{x}10^{31}$ sec^{-1} at 1 AU [4] and the scale for its structure in the ionosphere is large, so the temporal variations can take much longer than in other (smaller) comets with production rates up to few 10^{29} sec^{-1}. Numerical modeling of the solar wind interaction with comet Hale-Bopp [3] shows the bow shock to form at $1.4\text{x}10^6$ km nucleocentric distance, and the formation of a diamagnetic cavity at about $1.5\text{x}10^4$ km in the direction of the sun, extending to $4.4\text{x}10^4$ km downstream (assuming G is 10^{31} s^{-1} at distance 1 AU). The comparison to the bow shock and cavity distances in comet Halley at the time of Giotto encounter (4 $\text{x}10^5$ km and 4 $\text{x}10^3$ km, respectively) shows Hale-Bopp to be about four times larger at the same perihelion point [14, 15, 16].

The present scheme used for solving the above system is the explicit three dimensional Lax-Wendroff method. By using this approach, one will have good accuracy for treating the system of equations (1 to 5) above, where this method is of accuracy of second order in space (Δx^2) and time (Δt^2).

The Lax-Wendroff method can be summarized in the following general scheme. Let us write the specified equation in the general form as below,

$$\frac{\partial Y}{\partial t} = -a\vec{\nabla}.\vec{E} \qquad (9),$$

where a can be any constant and $\boldsymbol{E}$ represents the specified physical quantity. Then, the application of Lax-Wendroff scheme [10] will result in the following equation for three-dimension model,

$$Y_{i,j,k}^{n+1} = Y_{i,j,k}^{n} - \frac{a\Delta t}{2}\left[\frac{E_{i+1,j,k}^{n} - E_{i-1,j,k}^{n}}{\Delta x} + \frac{E_{i,j+1,k}^{n} - E_{i,j-1,k}^{n}}{\Delta y} + \frac{E_{i,j,k+1}^{n} - E_{i,j,k-1}^{n}}{\Delta z}\right] +$$

$$\frac{a^2(\Delta t)^2}{8}\left\{\left[\frac{J_{i+1,j,k}^{n} - J_{i-1,j,k}^{n}}{\Delta x} + \frac{J_{i,j+1,k}^{n} - J_{i,j-1,k}^{n}}{\Delta y} + \frac{J_{i,j,k+1}^{n} - J_{i,j,k-1}^{n}}{\Delta z}\right]\times\right.$$

$$\left[\frac{E_{i+1,j,k}^{n} - E_{i-1,j,k}^{n}}{\Delta x} + \frac{E_{i,j+1,k}^{n} - E_{i,j-1,k}^{n}}{\Delta y} + \frac{E_{i,j,k+1}^{n} - E_{i,j,k-1}^{n}}{\Delta z}\right]\times$$

$$+ 2J_{i,j,k}^{n}\left[\frac{\left[E_{i+1,j+1,k}^{n} - E_{i+1,j-1,k}^{n}\right] - \left(E_{i-1,j+1,k}^{n} - E_{i-1,j-1,k}^{n}\right)}{\Delta x\Delta y} + \right.$$

$$\frac{\left(E_{i+1,j,k+1}^{n} - E_{i+1,j,k-1}^{n}\right) - \left(E_{i-1,j,k+1}^{n} - E_{i-1,j,k-1}^{n}\right)}{\Delta x\Delta z} +$$

$$\left.\frac{\left(E_{i,j+1,k+1} - E_{i,j+1,k-1}\right) - \left(E_{i,j-1,k+1} - E_{i,j-1,k-1}\right)}{\Delta y\Delta z}\right] + J_{i,j,k}^{n}\times$$

$$\left[\frac{\left[E_{i+1,j,k}^{n} - 2E_{i,j,k}^{n} + E_{i-1,j,k}^{n}\right]}{(\Delta x)^2} + \frac{\left[E_{i,j+1,k}^{n} - 2E_{i,j,k}^{n} + E_{i,j-1,k}^{n}\right]}{(\Delta y)^2} + \right.$$

$$\left. + \frac{\left[E_{i,j,k+1}^{n} - 2E_{i,j,k}^{n} + E_{i,j,k-1}^{n}\right]}{(\Delta z)^2}\right] \qquad (10).$$

where the *J*'s represent the Jacobians of the selected equation. For more details and applications of one-dimension computational scheme of this method, see ref. [10].

Then, eq.(10) was applied for in the present paper to the entire set of parameters of eqs.(1-5) above, resulting extremely complicated schemes. Although programming these schemes required comprehensive subroutines, the results show, however, that the effort is worthy, as shown below. A final remark that should be mentioned here is that Lax-Wendroff scheme is highly stable, thus it was chosen in the present simulation.

4. Results and Discussions

In the present paper, the different possible interactions between cometary tail and the solar wind in the present of the IMF have been studied. The model of simulation was achieved using Lax-Wendroff explicit method for three-dimensional space, and the results of the present simulation are shown in the Figures (1-6) below. These results are obtained from simulating a comet that has similar properties to comet Hale-Bopp. Specific properties of the present numerical calculations are shown in Table (1) below. These properties are taken from Rauer [4]. In addition, the properties of the solar wind at distance 1 AU are also given in this table. On the other hand, the computer program used in the present work has a set of initial and boundary conditions that are required to specify some of the physical properties of the present physical system (the comet tail + solar wind). Such initial and boundary conditions will determine basically both the starting and ending points of the results, but not the behavior of the system. This behavior must be found from solving the present set of numerical equations for the present system. Ideally, and if these values were wisely chosen within the logic limits of the case under study, then the system of equations above, eqs.(1 to 5), should behave in a similar way to the actual system.

Table(1). Properties of Comet Hale-Bopp and Solar Wind

COMET PROPERTIES			
$\sigma = 3.510^{-7}$ sec^{-1}	$\gamma = 1.667$	$G=10^{31}$ sec^{-1}	$R_I=10^9$ m
SOLAR WIND PROPERTIES			
$\rho_\Theta =5.0\ m_p$	u_Θ = 400.0 km /sec	m_c = 20 .0x m_p	v_c =1000 *km/sec*

These conditions were tested for initial and boundary values set similar to those found in the papers of Wegmann [7] and Schmidt-Voigt [8]. The code written for the present simulation (LW3D.m) needs such set of initial and boundary conditions because Lax-Wendroff explicit method must be controlled at the boundaries in order to achieve convergent behavior of the final results. The computer code for the present purpose was written in MATLAB program, and the initial and boundary conditions used here are shown in Table (2) below.

Table (2). Initial and boundary conditions of references [7, 8]

Parameter		Initial	Boundary
Mass density	ρ	1.00 x 10^{-21}	0.00
Particles velocity	v	1.00	10.00
Magnetic field	B	44.00 x 10^{-9}	10.00 x 10^{-9}
Internal energy	E	0.00	4.00 x 10^{-12}

The effect of the source term in the MHD equations represents the addition of new ions to the solar wind [7, 13, 15, 16]. Such effect will highly reproduce most of the properties of the comet tail, therefore changing the shape considerably due to the specifications of the comet nucleus properties. This will also make minor changes in the properties of the solar wind near the comet tail, but these changes are usually negligible because the flow of the solar wind which will soon wash-out these changes.

In the present simulation, the numerical grid was chosen to have 15x15 nodes in order to cover a region about 20x10^6 kilometers. The interaction length, R_I is found to be of order of 10^6 kilometers. The nucleus position was assumed at distance x=1 (units of R_I) in the computational grid.

The effect of the source terms is included until x=15 (units of R_I) so that the study includes a wide range of space surrounding the sun.

In Fig.(1) and Fig.(2) the results of particle density and number of particles, respectively, are given for two values of the z-axis (distance from the comet nucleus). These values of z correspond to 5xR_I and 14xR_I, which fairly shows the effect on these as we move away from the comet nucleus. At z=5 in both figures, the values were about one order of magnitude larger than at distance z=14. Therefore, these values were also chosen for the rest of the results.

The peak at the smaller values of the meshgrid represents the position of the cometary nucleus where the ions production is at its maximum. These peaks coincide in both figures of density and number of particles. In addition, it is seen from these figures that as the meshgrid develops away from the comet nucleus the values of the particle density and number of particles gradually are reduced.

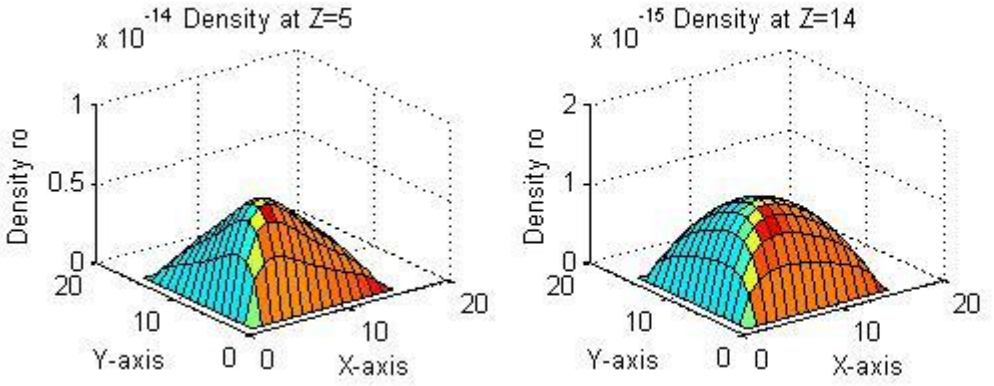

Fig.(1). The results of particle density from MHD simulation. The distances are in units of interaction length R_I. z represents the azimuthal distance from the comet nucleus.

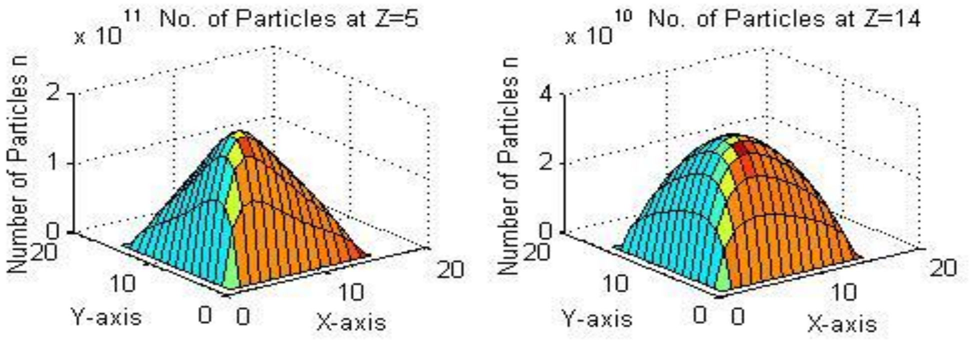

Fig.(2). The results of number of particles from MHD simulation. The distances are in units of interaction length R_I. z represents the azimuthal distance from the comet nucleus.

Physical interpretation of these results is as follows: when the solar wind hits the nucleus there will be intensive number of new particles (ions) generated and added to the structure of the solar system. Therefore, a peak is shown to be centered at the comet nucleus [5, 8]. As the distance from this center increases, these ions will go through the recombination process which may last for considerable lifetime [11, 12, 15, 16, 17]. This will lead to a gradual and slow decrement in the ions density as shown in both figures. Ideally, at a very large distance from the comet nucleus, solar wind must retain its original properties and the behavior returns to the original (unperturbed) system. This is not shown in Figs.(1) and (2) because the gas production rate, *G*, of comet Hale-Bopp is incredibly large (see Table 1 above). This indicates the necessity to perform future investigation for this come by means of numerical calculation in order to study the behavior of the tail at distances larger than the presently selected area (20x10^6 kilometers).

The results of speed of particles in the *x*-direction is shown in Fig.(3). These results are almost the same in the other two *y*- and *z*-directions, therefore only the results of the first direction are treated here. This similarity is obtained because the initial and boundary conditions were chosen the same for the present simulations, i.e., an assumption was made that velocity is isotropic in this case. This seems rather logic [7] since the comet Hale-Bopp starts generating its tail at large distance from the sun - more than 3 AU [4]-. At such large distances from the sun, solar wind should be moving with small speed comparing to the speed of the newly generated ions from the cometary nucleus [3, 4, 8, 18]. The behavior at different azimuthal distances is expected also and it physically means that as the distance increases away from the comet nucleus the particles velocity will gradually decrease. This particle velocity behavior indicates that velocity was subtracted in the region near the nucleus. The explanation is because the new ions generated from the comet nucleus will basically be pointed out symmetrically, i.e., in all directions with the same probability, which causes the vector sum of adding these velocities with the particles of the solar wind to decrease. This decrement is obviously seen from Fig.(3), where at the region next to the comet the velocity dropped to he minimum value.

Another remark that should be mentioned here is that Lax-Wendroff scheme in the case of velocity will result the same computational relations as Lax scheme. Lax scheme is of second order in space and first order accurate in time [10]. The Lax-Wendroff scheme, on the other hand, makes use of different types of Jacobians, as seen from eq.(10) above. The difference is eliminated in the case of velocity because the Jacobians are actually zero in this case. Therefore, Lax and Lax-Wendroff schemes are of the same accuracy in the case of velocity only.

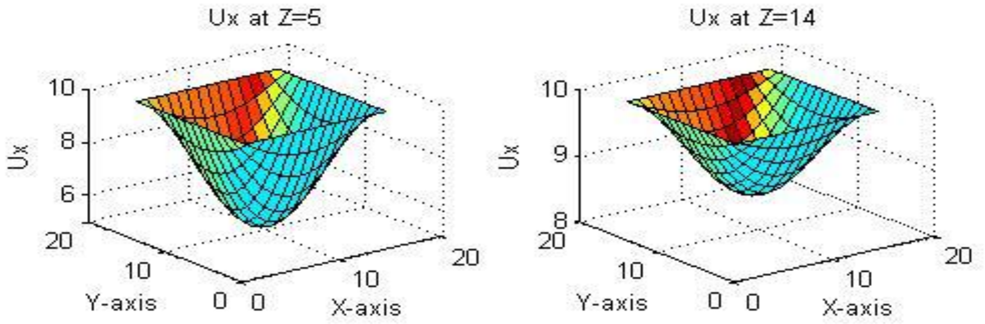

Fig.(3). The results of plasma velocity in the *x*-direction from MHD simulation. The distances are in units of interaction length R_I. *z* represents the azimuthal distance from the comet nucleus..

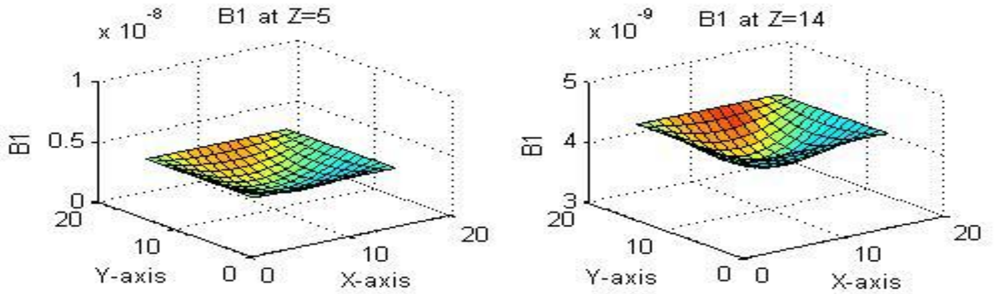

Fig.(4). The results of magnetic flux in the *x*-direction from MHD simulation. The distances are in units of interaction length R_I. *z* represents the azimuthal distance from the comet nucleus.

Fig.(4) shows the results of magnetic field in the *x*-direction. The Lorentz force exerted by the magnetic field on charged particles (ions generated from the cometary nucleus) will increase as the magnetic field increases. This will lead to the confinement of these particles in the magnetic field. The angle between the charged ions direction and that of the magnetic field will be zero in the same direction and one expects that the force due o magnetic field presence in this case will be zero. However, due to the fact that charged particles will in turn contribute to some degree in the strength of the IMF specially close to the comet nucleus [19, 20].

Therefore the expected behavior of the magnetic field is to suffer from certain weakness near the nucleus. This behavior is shown in Fig.(4) clearly, where at the position of the cometary nucleus a smooth droop in the magnetic strength is observed. As the vertical distance, *z*, increase, the magnetic field only slightly affected by the presence of the comet existence.

Finally, Figs.(5) and (6) show the results of plasma pressure and internal energy. These quantities are strongly related to each other as seen from eq.(5) above. As shown in fig.(5), the vertical distance strongly altered the behavior of the plasma pressure where at *z*=5 the results show that pressure decreased in the position centered at the comet nucleus, while at *z*=14 the pressure *increased*. This is explained on the bases of the conservation of energy which states that as the internal energy decreases the pressure must also decrease. Joining the results of Fig.(5) and (6) for *z*=5, this explanation is rather reasonable. In the region near the comet nucleus, most of the energy goes to kinetic energy while the internal energy decrease so that the amount of total energy remains the same.

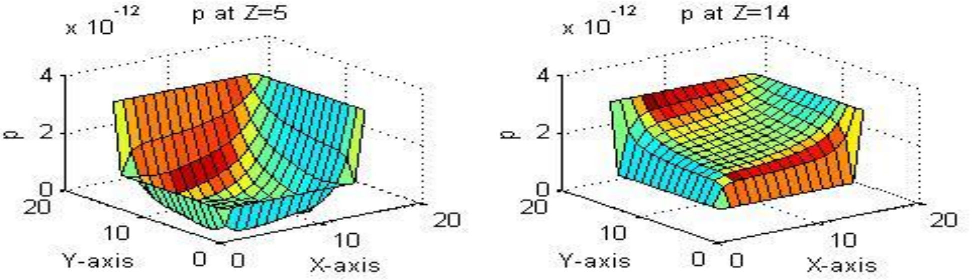

Fig.(5). The results of plasma pressure from MHD simulation. The distances are in units of interaction length R_I. *z* represents the azimuthal distance from the comet nucleus..

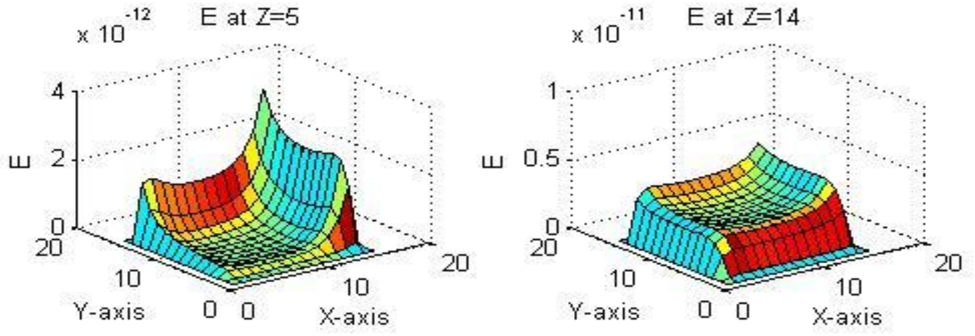

Fig.(6). The results of internal energy from MHD simulation. The distances are in units of interaction length R_I. z represents the azimuthal distance from the comet nucleus.

As the distance increases in the *xy* plane, the process is reversed because kinetic energy then will decrease due to continuous collisions of the generated ions with other (slow) particles of the solar wind. Therefore, internal energy will increase as seen from Fig.(6). This is accompanied with the sharp increment in the plasma pressure at large distances. On the other hand, as the vertical distance increases, the situation will seems as if the distance in the *xy* plane increased, resulting the same behavior described above for this case.

In the region just in front of the comet nucleus, the properties of the solar wind will not be affected because solar wind plasma will be heading from the sun towards the comet, while after the nucleus, the spectacular change is observed from the simulation results. In all cases, the resulted behavior was consistent with earlier papers [7, 8, 9, 18], where similar behavior was obtained and analyzed.

5. Conclusions

The interaction between comet Hale-Bopp tail with the plasma of the solar wind was sided by means of MHD numerical simulation. The simulation was based on three-dimensional Lax-Wendroff explicit scheme, providing second-order accuracy in space and time.

The results show that the main effect in the interaction is due to the ions produced from the nucleus of the comet which add important effects on the microstructure of the solar wind. These changes were investigated and analyzed for three-dimensional space, where the present simulation of the behavior was made for Hale-Bopp's tail at 1 AU from the sun. These properties include the changes of the plasma density, particle velocity, IMF changes, pressure, and internal energy. The results indicated that plasma density increased significantly near the comet nucleus, as well as the number of particles, and these results were explained on the bases of the source term effects. Particle velocity behaved as if the velocity was subtracted in the region near the nucleus because ions generated from the comet nucleus will basically be pointed out symmetrically, which causes the vector sum of adding these velocities with the particles of the solar wind to decrease. Magnetic field, pressure and internal energy results all indicated the dynamic effects of these new ions and the results were properly attributed to the changes in the solar wind properties near the comet nucleus.

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محاكاة الماغنيتوهيدروديناميك ثلاثية الأبعاد لذيل المذنب هايل – بوب

د.سلمان زيدان خلف* ***أحمد عبد الرزاق سلمان*****

* قسم الفلك–كلية العلوم– جامعة بغداد

** قسم الفيزياء–كلية العلوم– جامعة بغداد

الخلاصة

في البحث الحالي تمت دراسة التفاعل بين ذنب المذنب والرياح الشمسية باستخدام محاكاة رقمية تعتمد على نموذج الماغنيتوهيدروديناميك (MHD) والذي يأخذ بنظر الاعتبار تأثير المجال المغناطيسي ما بين الكواكب (IMF). هذه المحاكاة تعتمد على طريقة لأكس–ويندروف لثلاثة أبعاد، والتي توفر دقة من المرتبة الثانية في الفضاء والزمن. أن الايونات المتولدة من نواة المذنب ستضيف تأثيرا مهما على التركيب الداخلي للرياح الشمسية، ولذلك سيحصل تغير كبير على الخواص الفيزيائية لتلك الرياح. المحاكاة الحالية تدرس تلك التغيرات بعناية عن طريق محاكاة التفاعل بين ذيل المذنب هايل–بوب على مسافة وحدة فلكية واحدة من الشمس. هذه الخواص تشمل الكثافة الأيونية، سرعة الجسيمات، المجال المغناطيسي، ضغط البلازما والطاقة الداخلية. بينت النتائج بوضوح أن التغير الحاصل في مواصفات الرياح الشمسية يستمر لمسافات كبيرة. هذه التغيرات أوضحت التأثير المهم لتضمين وجود المصدر الأيوني في النموذج الخاص. أظهرت النتائج أن الرياح الشمسية تستعيد معظم خواصها الأولية على مسافات كبيرة من نواة المذنب. أيضا تمت مقارنة نتائج البحث الحالي مع بحوث سابقة. المحاكاة الحالية تمت باستخدام برنامج الماتلاب.