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EVOLUTION OF DENSITY PERTURBATIONS IN A CYLINDRICAL MOLECULAR CLOUD USING SMOOTHED PARTICLE HYDRODYNAMICS

M. Nejad-Asghar[1,2]**, J. Soltani**[1]

[1]*Department of Physics, University of Mazandaran, Babolsar, Iran*

[2]*Department of Physics, Damghan University of Basic Sciences, Damghan, Iran*

E–mail: *nejadasghar@umz.ac.ir*

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SUMMARY: Molecular clouds have a hierarchical structure from few tens of parsecs for giants to few tenth of a parsec for proto-stellar cores. Nowadays, our observational techniques are so advanced that it has become possible to detect the small-scale substructures inside the molecular cores. The question that arises is how these small condensations are formed. In the present research, we study the effect of ambipolar diffusion heating on the ubiquitous perturbations in a molecular cloud and investigate the possibility of converting them to dense substructures. For this purpose, a small azimuthal perturbation is implemented on the density of an axisymmetric two-dimensional cylindrical cloud, and its evolution is simulated by the technique of two-fluid smoothed particle hydrodynamics. The self-gravity is not included and the initial state has uniform density, temperature and magnetic field, parallel to the axis of cylinder. In addition, all perturbed quantities are assumed to depend only on azimuth angle and time. Computer experiments show that if the ambipolar diffusion heating is ignored, the perturbation will be dispersed over the time. Including the heating due to ambipolar diffusion heats the matter in regions adjacent to the perturbation, thus, leading to the transfer of matter into the perturbed area. In this case, the density of perturbations can be increased. Also, the results of simulations show that an increase of the initial magnetic pressure leads to the intensification of difference between density of perturbations and their surroundings (i.e. increasing of density contrast). This effect is due to the direct relationship of the drift velocity to the intensity of the magnetic field and its gradient. Simulations with different initial uniform densities show that the growth of relative density contrast is more clear with a special density. This result can be explained by the intensification of thermal instability in this special density.

Key words. ISM: clouds – evolution – ISM: magnetic fields – Stars: formation – Methods: numerical

1. INTRODUCTION

All molecular clouds are observed as fuzzy patches with hierarchical substructures. The smallest features are named dense cores, which are to be expected as simplest star-forming sites (André et al. 2008). Our observational techniques are nowadays so advanced that our domain of information is extended into these molecular cores (e.g.

Tafalla 2008). Although, dimensions of the cores are so small that we cannot directly observe inside them with telescopes, a lot of information on their small-scale substructures has been obtained via indirect methods. For exammple, Peng et al. (1998) investigated the substructures in a core of Taurus molecular cloud (TMC-1), and found entities with scales of a few hundredths of a parsec inside them. Shinnaga et al. (2004) made a synthesis imaging to reveal clumpy substructures inside starless cores of Taurus molecular cloud L1521F. Recent observations of Pirogov and Zinchenko (2008), of line profiles of HCN(1-0) and CS(2-1), emanated from dense cores of M17-SW and Orion A, show that there are few hundred thousand dense points in each core with scale of few tenth of a parsec. Also, we can quote the observations of Heithausen et al. (2008) who used comparative data analysis of molecular lines and dust continuum at 1.2 mm, to reveal the few thousand AU-scale substructures in the embedded proto-stellar core at MCLD123.5+24.9. In any case, nowadays, there is no doubt that the small-scale substructures exist inside molecular cores. Thus, it is a challenging task to present a suitable theoretical model for the formation of these substructures.

Observations have shown that molecular clouds are generally turbulent (e.g. Elmegreen and Scalo 2004), thus, the first idea that may be analysed in terms of the formation of substructures is the effect of turbulence. Can turbulence be considered as an important agent in the formation of small-scale substructures in the molecular cores? Although molecular clouds are generally turbulent, the analysis of the data from the interior of dense cores show that they are not exactly turbulent, since they are characterized by subsonic infall motions (e.g. Lee et al. 2004) and small velocity gradient (e.g. Caselli et al. 2002). Also, turbulence must be continually pumped by some external energy source to prevent rapid decay. The nature of that source is unknown. Thus, we cannot consider the turbulence as the only agent for the formation of the small-scale substructures in all molecular cores. As another possibility, Van Loo et al. (2007) implemented a two-dimensional simulation with the idea that the mechanism giving rise to substructures is the same as the mechanism causing core formation (i.e. hydromagnetic waves). Substructures obtained in their simulation are in good agreement to the observed substructures of core D of TMC-1. Thus, the dynamical mechanisms like hydromagnetic waves or turbulence can be considered as explaining sources for substructures in dense cores, we must not neglect some non-dynamical processes and instabilities such as thermal instability.

Many papers have been published on thermal instability in partially ionized medium such as molecular clouds (e.g. Gilden 1984, Birk 2000, Falle et al. 2006, van Loo et al. 2007, Fukue and Kamaya 2007). Magnetic field is the inseparable part of the interstellar medium, and it also permeates partially in the molecular clouds. Effect of magnetic field in evolution of molecular clouds is indirect, because the magnetic field is threaded only to the charged particles, and the ionization fraction is small. This phenomenon causes ambipolar diffusion of charged particles, so that the frictional drag force between charged and neutral particles can heat the medium (Scalo 1977). Since thermal instability is sensitive to cooling and heating functions, considering of heating due to ambipolar diffusion leads to the occurrence of thermal instability in some regions of molecular clouds (Nejad-Asghar 2007). Also, Nejad-Asghar and Molteni (2008) have recently investigated thermal phases of a molecular cloud layer by a simulation using two-fluid smoothed particle hydrodynamics (SPH). Their simulation confirms the results of linear investigation by Nejad-Asghar (2007). They show that considering of heating due to ambipolar diffusion leads to the occurrence of thermal instability and formation of condensations, in the middle and outer parts of the layer.

In this research we want to simulate the effect of heating due to ambipolar diffusion and occurence of thermal instability in two-dimensional case. For this purpose, we use a cylindrical molecular cloud with axial magnetic field and consider azimuthal perturbations therein. The self-gravity is not included, and the initial state has uniform density, temperature and magnetic field, which is parallel to the axis of cylinder (in the z direction). In addition, all perturbed quantities are assumed to depend only on azimuth angle (θ) and time (t). We investigate the evolution of these perturbations using two-fluid SPH as outlined by Nejad-Asghar and Molteni (2008). In Section 2, cooling of molecular clouds and heating due to ambipolar diffusion are described, and the numerical scheme is explained. Section 3 pertains to the simulation experiments, in which the initial setup of the cloud is discussed and the results presented. Finally, Section 4 is devoted to a summary and conclusion.

2. GAS DYNAMICS AND NUMERICAL METHOD

The molecular clouds, in reality, are very weakly ionized. The ion density can be approximated by the expression

$$\rho_i = \epsilon(\rho_n^{1/2} + \epsilon' \rho_n^{-2}), \tag{1}$$

which was used by Fiedler and Mouschovias (1992). In standard ionized equilibrium state, one has $\epsilon \sim 7.5 \times 10^{-15}\mathrm{kg}^{1/2}\mathrm{m}^{-3/2}$ and $\epsilon' \sim 4 \times 10^{-44}\mathrm{kg}^{5/2}\mathrm{m}^{-15/2}$. In general, the ion velocity $\mathbf{v}_i$ and the neutral velocity $\mathbf{v}_n$ in molecular clouds should be determined by solving separate fluid equations for these species, including their coupling by collision processes with collisional drag $\gamma_{\mathrm{AD}} \sim 3.5 \times 10^{10}\mathrm{m}^3\mathrm{kg}^{-1}\mathrm{s}^{-1}$ (Shu 1992). The two fluids of ion and neutral are decoupled with a drift velocity, approximately given by

$$\mathbf{v}_{\rm d} \equiv \mathbf{v}_i - \mathbf{v}_n \approx \frac{1}{\mu_0 \gamma_{\rm AD} \rho_i \rho_n} (\nabla \times \mathbf{B}) \times \mathbf{B}, \qquad (2)$$

which is obtained in the assumption that for the charged fluid component, all forces (pressure, gravitation, ...) are negligible compared to the Lorentz and collisional drag forces, because of the low ionization fraction (Shu 1992).

Determining the cooling rate for an optically thick, dusty molecular medium is a complex non-LTE radiative transfer problem. Here, we use the parameterized cooling function as outlined by Goldsmith (2001),

$$\Lambda_{(n,T)} = \Lambda_{(n)} \left(\frac{T}{10{\rm K}}\right)^{\beta_{(n)}}, \qquad (3)$$

who computed the cooling effects of the molecular depletion from the gas phase on grain surfaces in dark clouds, and gave the value of parameters for different depletion runs. Nejad-Asghar (2007) fitted a polynomial function for these parameters as follows

$$\log\left(\frac{\Lambda_{(n)}}{{\rm J.kg^{-1}.s^{-1}}}\right) = -8.98 - 0.87(\log\frac{n}{n_0}) - 0.14(\log\frac{n}{n_0})^2, \qquad (4)$$

$$\beta_{(n)} = 3.07 - 0.11(\log\frac{n}{n_0}) - 0.13(\log\frac{n}{n_0})^2, \qquad (5)$$

where $n_0 = 10^{12}{\rm m^{-3}}$.

There are several different heating mechanisms in the models of interstellar matter. In dense molecular clouds, the most prominent one is heating due to cosmic rays, which can be approximated as $\Gamma_{\rm CR} \approx 3.12 \times 10^{-8}$ $\rm Jkg^{-1}s^{-1}$ (e.g. Glassgold and Langer 1973). Another important heating mechanism in the dense molecular clouds is the heating produced by the magnetic ion slip (ambipolar diffusion), which was examined by Scalo (1977) for density dependence of the magnetic field in a fragmenting molecular cloud. The volumetric rate of ambipolar diffusion heating is defined in terms of the drag force per unit volume $\mathbf{f}_d = \gamma_{\rm AD}\rho_i\rho_n\mathbf{v}_d$, exerted between neutral and ion fluids. The general formula for this volumetric heating rate is given by

$$\Gamma_{\rm AD} = \frac{\mathbf{f}_{\rm d}.\mathbf{v}_{\rm d}}{\rho_n}, \qquad (6)$$

where we use the approximation $\rho_n + \rho_i \approx \rho_n$. Therefore, in this research, we apply the net cooling function $\Omega_{(\rho,T)}$,

$$\Omega_{(\rho,T)} \equiv \Lambda_{(n)}(\frac{T}{10{\rm K}})^{\beta_{(n)}} - (\Gamma_{\rm CR} + \Gamma_{\rm AD}). \qquad (7)$$

We consider a cylindrical lightly ionized molecular gas with purely axial magnetic field. The cylinder is assumed to be in the radial hydrostatic equilibrium, thus all variables are functions of azimuth θ and time t only (see Fig. 1). In this arrange, the drift velocity (2) reduces to

$$\mathbf{v}_{\rm d} = -\frac{1}{\gamma_{\rm AD}\rho_n\rho_i}\frac{1}{r}\frac{\partial}{\partial\theta}\left(\frac{B^2}{2\mu_0}\right)\hat{\theta}. \qquad (8)$$

In presenting by angular velocity $\omega \equiv v/r$, the SPH form of drift velocity of ion particle a, as outlined by Nejad-Asghar and Molteni (2008), is given by

$$\omega_{{\rm d},a} = \frac{1}{\gamma_{\rm AD}\rho_{n,a}\, r_a}[-\frac{1}{2\mu_0\rho_{i,a}}\sum_b \frac{m_b}{\rho_{i,b}}(B_b^2 - B_a^2) \times \frac{dW_{ab}}{d\theta_a} - \rho_{i,a}\sum_b \frac{m_b}{\rho_{i,b}}\Pi_{ab}\frac{dW_{ab}}{d\theta_a}] \qquad (9)$$

where Π_{ab} is the usual artificial viscosity between ion particles a and b. The neutral density in place of neutral particles is estimated via usual summation over neighboring neutral particles $\rho_{n,\alpha} = \sum_\beta m_\beta W_{\alpha\beta}$, while in place of ions, $\rho_{n,a}$, is given by interpolation technique from the values of nearest neighbors. The ion density is evaluated via Eq. (1) for both places of ions and neutral particles.

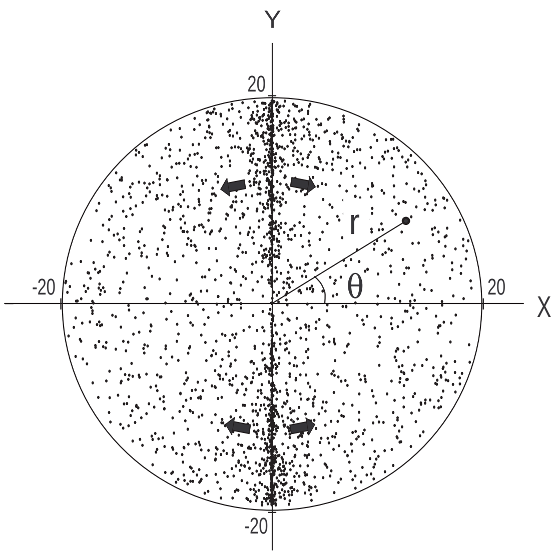

Fig. 1. *Schematic diagram of SPH particle distributed in a cylindrical molecular cloud. Note that some particles are picked out for clear representation. The black-arrows indicate the drift velocity of ions moving from dense regions to the adjacent area.*

The magnetic induction equation,

$$\frac{dB}{dt} = -\frac{1}{r}\frac{\partial}{\partial\theta}(Bv_{\rm d}) - \frac{\partial}{\partial\theta}(B\omega), \qquad (10)$$

and evolution of momentum,

$$\frac{d\omega}{dt} = -\frac{1}{\rho r^2}\frac{\partial}{\partial\theta}\left(p + \frac{B^2}{2\mu_0}\right), \qquad (11)$$

can be transformed to the form of SPH, as follows

$$\frac{dB_a}{dt} = \sum_b \frac{m_b}{\rho_{i,b}} B_a \omega_{ab} \frac{dW_{ab}}{d\theta_a}, \tag{12}$$

$$\frac{d\omega_\alpha}{dt} = -\frac{1}{r_\alpha^2} \sum_\beta m_\beta (\frac{p_\alpha}{\rho_\alpha^2} + \frac{p_\beta}{\rho_\beta^2} + \Pi_{\alpha\beta}) \frac{dW_{\alpha\beta}}{d\theta_\alpha} + \dot{\omega}_{\mathrm{drag},\alpha}, \tag{13}$$

respectively, where $\dot{\omega}_{\mathrm{drag},\alpha} = \gamma_{\mathrm{AD}} \rho_{i,\alpha} \omega_{d,\alpha}$ is the drag acceleration exerted on neutrals due to ambipolar diffusion of charged particles, and pressure is given by the ideal gas equation of state $p = (R/\mu)\rho T$. The molecular cloud is assumed as global neutral which consists of a mixture of atomic and molecular hydrogen (with mass fraction X), helium (with mass fraction Y), and traces of CO and other rare molecules, thus, the mean molecular weight is given by $1/\mu = X/2 + Y/4$.

The ion momentum equation assumes instantaneous velocity update, so that we have

$$\omega_a = \sum_\beta \frac{m_\beta}{\rho_\beta} \omega_\beta W_{\alpha\beta} + \omega_{\mathrm{d},a}, \tag{14}$$

where the first term on the right-hand side gives the neutral velocity field at the ion particle a, calculated using the standard SPH approximation. Finally, the energy equation,

$$\frac{du}{dt} = -\frac{p}{\rho} \frac{\partial v}{\partial z} - \Omega_{(\rho,T)}, \tag{15}$$

can be converted to the form of SPH, as follows

$$\frac{du_\alpha}{dt} = \frac{1}{2} \sum_\beta m_\beta (\frac{p_\alpha}{\rho_\alpha^2} + \frac{p_\beta}{\rho_\beta^2} + \Pi_{\alpha\beta}) \omega_{\alpha\beta} \frac{dW_{\alpha\beta}}{d\theta_\alpha} - \Omega_\alpha. \tag{16}$$

3. SIMULATION EXPERIMENTS

The chosen physical scales for length and time are $[l] = 200$AU, and $[t] = 10^3$yr, respectively, so that velocity unit is approximately $[v] = 1$ kms^{-1}. The gravitational constant has dimensions $G = 1[m]^{-1}[l]^3[t]^{-2}$, and the calculated mass unit is $[m] = 4.5 \times 10^{29}$kg. Consequently, the derived physical scales for density and energy per unit mass are $[\rho] = 1.7 \times 10^{-11}$kgm^{-3} and $[u] = 10^6$Jkg^{-1}, respectively. Specifying $\mu_0 = 1$, therefore, scales the unit of magnetic field to $[B] = 5.1$ nT. The simulations assume a cylindrical molecular core with purely axial magnetic field. The cylinder (with radius 0.02 pc) is in the radial hydrostatic equilibrium as indicated in Fig. 1. The initial condition for its uniform density is chosen in the interval 10^9m^{-3} to 10^{12}m^{-3}. We choose a molecular cloud which has mass fractions of molecular hydrogen and helium $X = 0.75$ and $Y = 0.25$, respectively, and has an initial uniform temperature of $T_0 = 20$K. The initial intensity of axial uniform magnetic field is expressed by the ratio of thermal to magnetic pressure $\beta \equiv p_{gas}/p_{mag}$.

We perturb the initial uniform-density system by giving the particles an $m = 2$ azimuthal perturbation, which has amplitude $A = 10$ percent. This is achieved by changing the cylindrical azimuthal coordinate θ of each particle to a value θ^* given by

$$\theta = \theta^* + \frac{A \sin(m\theta^*)}{m}. \tag{17}$$

The magnetic field is also likely to be perturbed. For simplicity, we assume that the perturbation does not affect the shape of the field lines. We do, however, adjust the field strengths of the particles to account for the perturbation. This is achieved by assuming the new field strength to be

$$B_{z,0}^* = B_{z,0} \left(\frac{\rho_i^*}{\rho_i}\right)^{1/2}, \tag{18}$$

where we have used the relationship between density and magnetic field strength given in Ciolek and Mouschovias (1995), ρ_i is the initial ion density and ρ_i^* is the perturbed ion density. Eq. (18) represents a compromise between the two extreme possibilities, namely (i) that the field is unperturbed and (ii) that the field is perturbed as if it were frozen in the gas perturbation.

In the first step, we consider a cylindrical cloud with initial uniform density $5.6 \times 10^{-4}[\rho]$ and without magnetic field ($\beta^{-1} = 0$). Simulation reveals that the exerted perturbations, on the basis of Eq. (17), disappear over the time. The disappearance time is comparable with the sound speed crossing time-scale. This is the most logical inference which is deduced from the balance of pressure difference, and accurately confirms the result of simulation. In the next step, the aforementioned cylindrical cloud is magnetized by a uniform axial magnetic field with initial intensities equivalent to $\beta^{-1} = 2.5$ and $\beta^{-1} = 10$, respectively. The perturbation of magnetic field is also evaluated on the basis of Eq. (18). The initial drift velocity of SPH particles versus azimuthal angles are shown in Fig. 2a. Since heating due to ambipolar diffusion is proportional to the square of drift velocity, inclusion of magnetic field leads to heating the adjacent region of perturbation, and transport of matter to the cooler perturbed regions. This is shown in Fig. 2b, in which the temperature of SPH particles are depicted versus the azimuthal angles, at different simulation times. As seen, temperature of particles around the perturbation increases so that the matter is, in isobaric case, transferred to the low-temperature area.

Displacement of matter from one region to another leads to density differences. Density contrast is defined as the difference between density maxima and minima. Fig. 3 shows density contrast at simulation time 20 $[t]$ for three values of β. In the case of $\beta^{-1} = 0$, the magnetic field is neglected and, as discussed previously, the balance of pressure difference leads to the gradual disappearance of perturbations so that the density contrast diminishes. Considering of magnetic field and ambipolar diffusion causes the displacement of matter into perturbations so that density contrast increases. Certainly, as shown in Fig. 3, increase of density contrast oscillates along with amplification of the amplitude. This phenomenon clearly is caused by the advent of MHD shock waves.

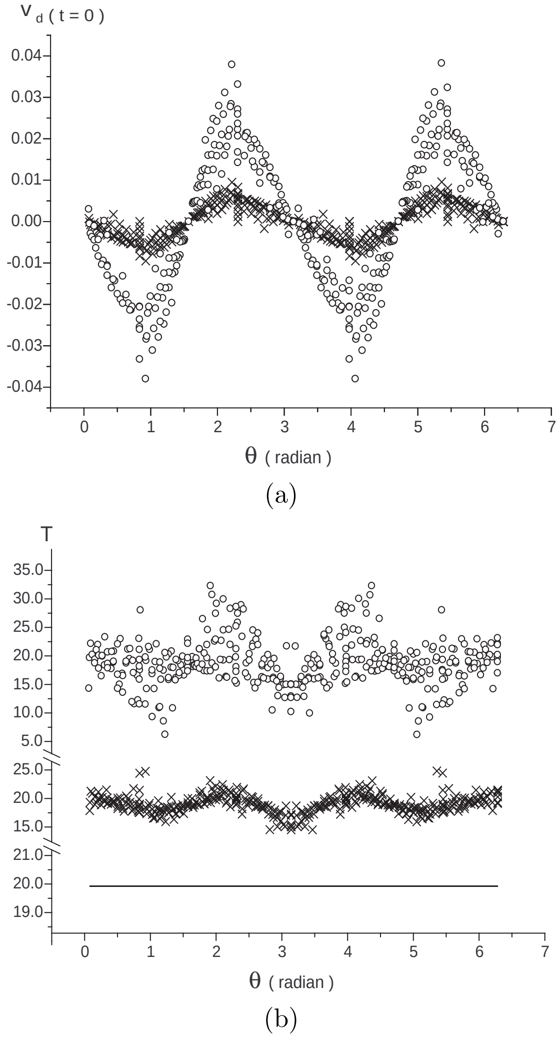

Fig. 2. *(a) Initial drift velocity (in unit of $[v]$) for two values of ratio of thermal to magnetic pressure $\beta^{-1} = 2.5$ (crosses) and $\beta^{-1} = 10$ (open circles). (b) Temperature of the cloud versus its azimuth angle at simulation times $t = 0$ (solid line), $t = 10[t]$ (crosses), and $t = 20[t]$ (open circles) for $\beta^{-1} = 10$.*

In view of the fact that heating due to ambipolar diffusion is inversely related to the local density of cloud, changing the initial density causes the alternation of the density contrast. We performed various experiments to investigate the evolution of perturbations in a magnetized cylindrical cloud with $\beta^{-1} = 2.5$, for initial uniform density from $10^9 \mathrm{m}^{-3}$ to $10^{12} \mathrm{m}^{-3}$. Maximum value of the relative density contrast, at simulation time 20 $[t]$, is shown in Fig. 4. The relative density contrast increases in a special density. This increase can be explained by the intensification of thermal instability occurring at that special density.

4. SUMMARY AND CONCLUSION

In this paper, the effect of heating due to ambipolar diffusion in evolution of ubiquitous perturbations in the molecular clouds was investigated. We used the two-dimensional cylindrical cloud with uniform initial density, which is in radial balance. The azimuthal perturbations, with ten percent amplitude, were imposed on the density of cloud, and their evolution was studied using two-fluid SPH technique. Without consideration of the magnetic field, balance of pressure difference causes the vanishing of perturbations over the time.

After applying uniform axial magnetic field to the cylindrical cloud, ambipolar diffusion heating leads to the increase of the temperature of the regions adjacent to perturbation. Thus, matter is, in the isobaric case, transferred to the cooler perturbed regions. This process, which is physically realized in oscillating case along with the amplification of the amplitude, leads to the increase of difference between density maxima and minima. This is shown in Fig. 3 as changing of density contrast.

We have simulated the evolution of perturbations in various computer experiments with various initial uniform densities. Results show that relative density contrast will increase at a special density. This increase can be justified by the intensification of the instability mechanism. Increase of the relative density contrast at special density can be used to explain the formation of small-scale substructures in central and outer regions of molecular cores where density reaches values of the order of 10^{11} m^{-3}.

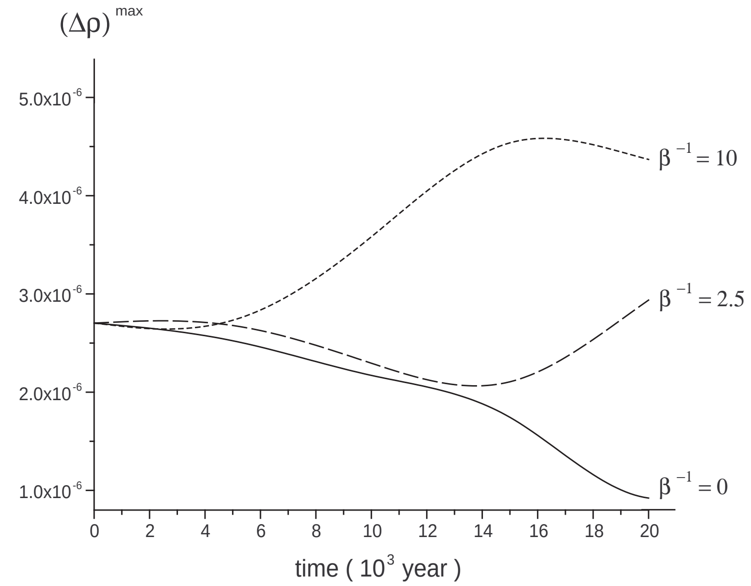

Fig. 3. *Evolution of the density contrast (in unit of* $[\rho]$*) for three values of ratio of thermal to magnetic pressure* β*.*

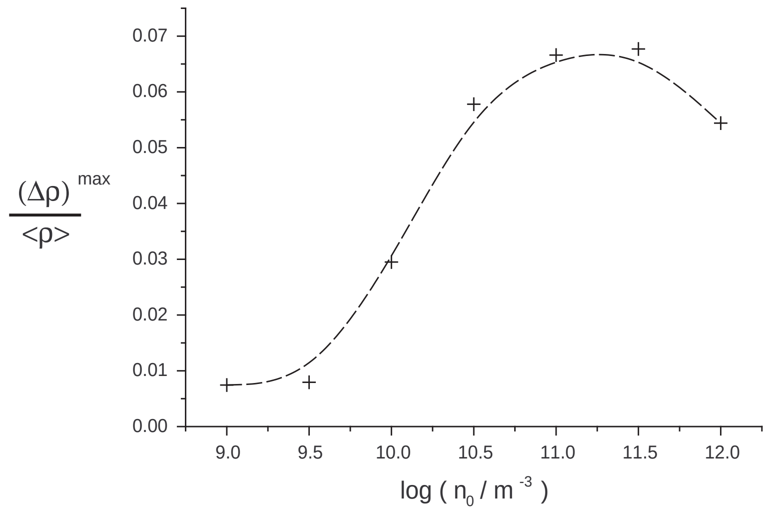

Fig. 4. *Maximum value of the relative density contrast at simulation time* $t = 20[t]$ *for different initial densities and with* $\beta^{-1} = 2.5$*. The simulated results are depicted by crosses, and the dashed curve is the B-spline fit on them.*

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ЕВОЛУЦИЈА ПОРЕМЕЋАЈА ГУСТИНЕ У ЦИЛИНДРИЧНОМ МОЛЕКУЛАРНОМ ОБЛАКУ УПОТРЕБОМ SPH (SMOOTHED PARTICLE HYDRODYNAMICS) МЕТОДЕ

M. Nejad-Asghar[1,2], **J. Soltani**[1]

[1] *Department of Physics, University of Mazandaran, Babolsar, Iran*

[2] *Department of Physics, Damghan University of Basic Sciences, Damghan, Iran*

E–mail: *nejadasghar@umz.ac.ir*

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Оригинални научни рад

Молекуларни облаци имају хијерархијску структуру од гигантских, више десетина парсека великих, до малих протозвезданих језгара величине једне десетине парсека. Данас су наше посматрачке технике толико напредовале да се могу детектовати подструктуре на малим скалама унутар језгара молекуларних облака. Питање је како су та мала згушњења настала. У овом истраживању је изучаван ефекат загревања амбиполарном дифузијом свуда присутних поремећаја у молекуларном облаку и истражена је могућност њиховог претварања у густе подструктуре. За ову сврху, мали азимутални поремећаји примењени су на густину унутар осносиметричних, дводимензионалних цилиндричних облака и њихова еволуција је симулирана методом двофлуидне SPH (smoothed particle hydrodynamics). Нумерички експерименти показују да ако се загревање амбиполарном дифузијом не разматра, поремећаји ће се растурити са проласком времена и густина облака ће бити хомогенизована. Разматрање загревања за које је одговорна амбиполарна дифузија доводи до тога да се материја у околним поремећајним регионима загрева и самим тим долази до трансфера материје у поремећену област. На овај начин, густина поремећаја може да расте. Резултати симулација показују да пораст почетног магнетног притиска доводи до интензивирања разлике између густине у поремећеном медијуму у односу на густину околине (тј. до пораста контраста густине). Овај ефект је заснован на директној зависности између брзине дрифта и јачине магнетног поља и његовог градијента. Симулације са различитим почетним густинама показују да је пораст релативног контраста густине уочљивији у посебној густини. Овај резултат може бити објашњен интензификацијом термалне нестабилности у посебној густини.