Hydrodynamic simulation coupled to chemical evolution in the star forming regions

Liton Majumdar[1], Ankan Das[1], Sandip K Chakrabarti[1,2], Sonali Chakrabarti[1,3]

1. Indian Centre for Space Physics, 43 Chalantika, Garia Station Rd., Kolkata-700084, India.

2. S. N. Bose National Centre for Basic Sciences, Salt Lake, Kolkata-700098, India.

3. Maharaja Manindra Chandra College, 20 Ramakanto Bose Street, Kolkata-700003, India.

Abstract

Chemical composition of a molecular cloud is highly sensitive upon the physical properties around that region. In order to have the more realistic knowledge around the star forming region, a two dimensional hydrodynamical flow is considered during the collapsing phase of a proto-star. Total variation diminishing scheme (TVD) is used to solve the set of hydrodynamical equations. Arm with this sophisticated hydrodynamical model, we couple our reasonably large chemical network including gas phase as well as grain phase chemical network, to study the chemical evolution during collapse of a protostar. Chemical evolution are studied by assuming constant temperature throughout the simulation as well as considering the temperature variation from the hydrodynamical model. It is noticed that Simulation results are highly sensitive upon the dynamic behavior of the collapsing Cloud.

Development of the TVD Model

We solve the following hyperbolic system of conservation equations for a collapsing interstellar cloud

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_k}(\rho u_k) = 0,$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial}{\partial x_k}(\rho u_i u_k + p\delta_{ik}) = 0$$

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial x_k}[(E+p)u_k] = 0,$$

Following Ryu et al., corresponding eigenvalues obtained from these equations

$$a_1 = v_x - c,\ a_2 = v_x,\ a_3 = v_x,\ a_4 = v_x,\ a_5 = v_x + c,$$

Left and right eigenvectors corresponding to eigenvalues

$$L_1 = \left[\frac{(\gamma-1)}{2\gamma} + \frac{v_x}{2c}, -\frac{1}{2c^2}, 0, 0, \frac{\rho}{2\gamma S}\right],$$

$$L_2 = [-v_y, 0, 1, 0, 0],$$

$$L_3 = \left[\frac{1}{\gamma}, 0, 0, 0, -\frac{\rho}{\gamma S}\right],$$

$$L_4 = [-v_z, 0, 0, 1, 0],$$

$$L_5 = \left[\frac{(\gamma-1)}{2\gamma} - \frac{v_x}{2c}, \frac{1}{2c^2}, 0, 0, \frac{\rho}{2\gamma S}\right].$$

$$\boldsymbol{R_1} = \begin{pmatrix} 1 \\ v_x - c \\ v_y \\ v_z \\ S/\rho \end{pmatrix},$$

$$\boldsymbol{R_2} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix},$$

$$\boldsymbol{R_3} = \begin{pmatrix} 1 \\ v_x \\ v_y \\ v_z \\ -(\gamma-1)S/\rho \end{pmatrix},$$

$$\boldsymbol{R_4} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{pmatrix},$$

$$\boldsymbol{R_5} = \begin{pmatrix} 1 \\ v_x + c \\ v_y \\ v_z \\ S/\rho \end{pmatrix}.$$

We use Roe approximate Riemann solution (Roe, 1981) to get the averaged values of The physical quantities at the grid boundaries

$$\rho_{i+\frac{1}{2}} = \frac{\rho_i + \rho_{i+1}}{2},$$

$$v_{x,i+1/2} = \frac{\sqrt{\rho_i} v_{x,i} + \sqrt{\rho_{i+1}} v_{x,i+1}}{\sqrt{\rho_i} + \sqrt{\rho_{i+1}}},$$

$$v_{y,i+1/2} = \frac{\sqrt{\rho_i} v_{y,i} + \sqrt{\rho_{i+1}} v_{y,i+1}}{\sqrt{\rho_i} + \sqrt{\rho_{i+1}}},$$

$$v_{z,i+1/2} = \frac{\sqrt{\rho_i} v_{z,i} + \sqrt{\rho_{i+1}} v_{z,i+1}}{\sqrt{\rho_i} + \sqrt{\rho_{i+1}}},$$

$$S_{i+1/2} = \frac{\sqrt{\rho_i} S_i + \sqrt{\rho_{i+1}} S_{i+1}}{\sqrt{\rho_i} + \sqrt{\rho_{i+1}}},$$

$$c_{i+1/2} = \gamma S_{i+1/2} \rho_{i+1/2}^{\gamma-2}.$$

Key merit of this scheme is to achieve a high resolution and require less CPU time

Different Modeling parameters

Physical Parameters in real unit

Parameter	Value
Outer radius	10^{17}cm
Inner radius	10^{14}cm
Initial Density	10^{-28}gm/cm^3
Courant factor	0.1
Initial Core mass	1.99×10^{33}gm
Velocity at outer x boundary	-2.5×10^{4} cm/sec
Angular rotation at outer x boundary	10^{-14} sec^{-1}
Density at the outer x boundary	10^{-22}gm/cm^3
γ	5/3
Number of grids	64×64
Threshold radius	4.62×10^{14}

Parameters used to dimensionless the TVD code

Parameter	Value
Length	10^{17}cm
Velocity	3×10^{10}cm/sec
Density	10^{-22}gm/cm^{-3}
Time	3.33×10^{6}second

In order to present the results of the simulations for a concrete case, here We consider an interstellar cloud having a size of 10^{17} cm (i.e. 0.03 parsec) and divide the entire cloud into 64x64 logarithmically equal spaced grids along x and z direction. In the TVD code, we use dimensionless quantities with the density at the outer boundary as the unit of density and the length of the computational zone along the x-axis as the unit of length.

Dynamical variation

Density Distribution in the meridional plane

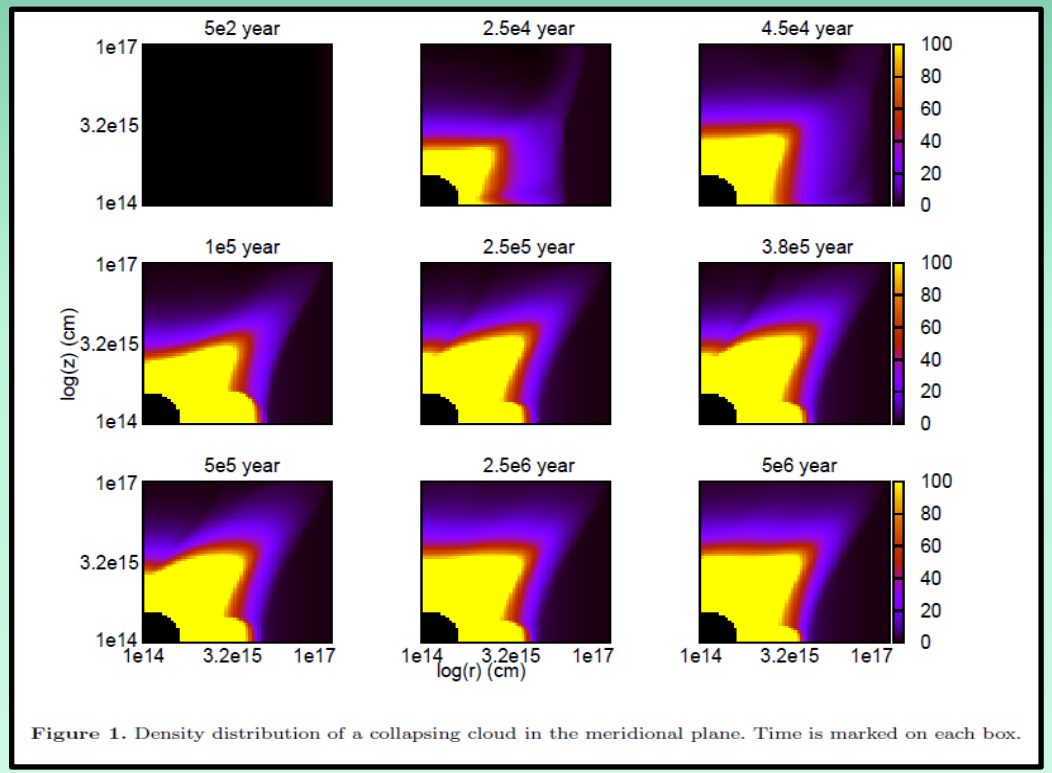


Figure 1. Density distribution of a collapsing cloud in the meridional plane. Time is marked on each box.

Temperature distribution throughout a plane

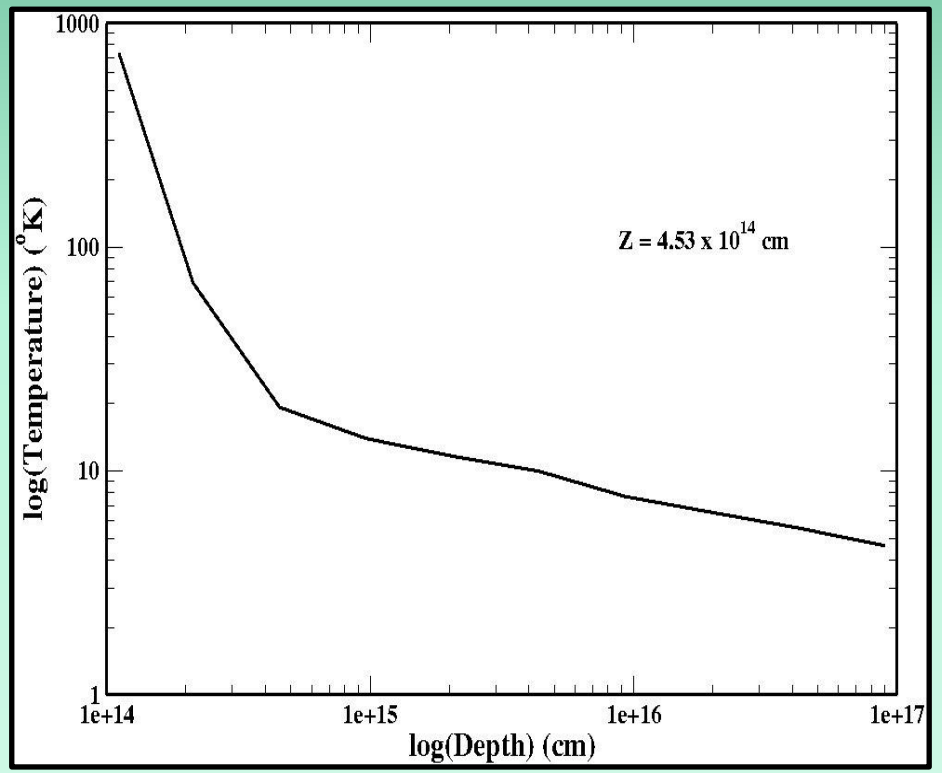
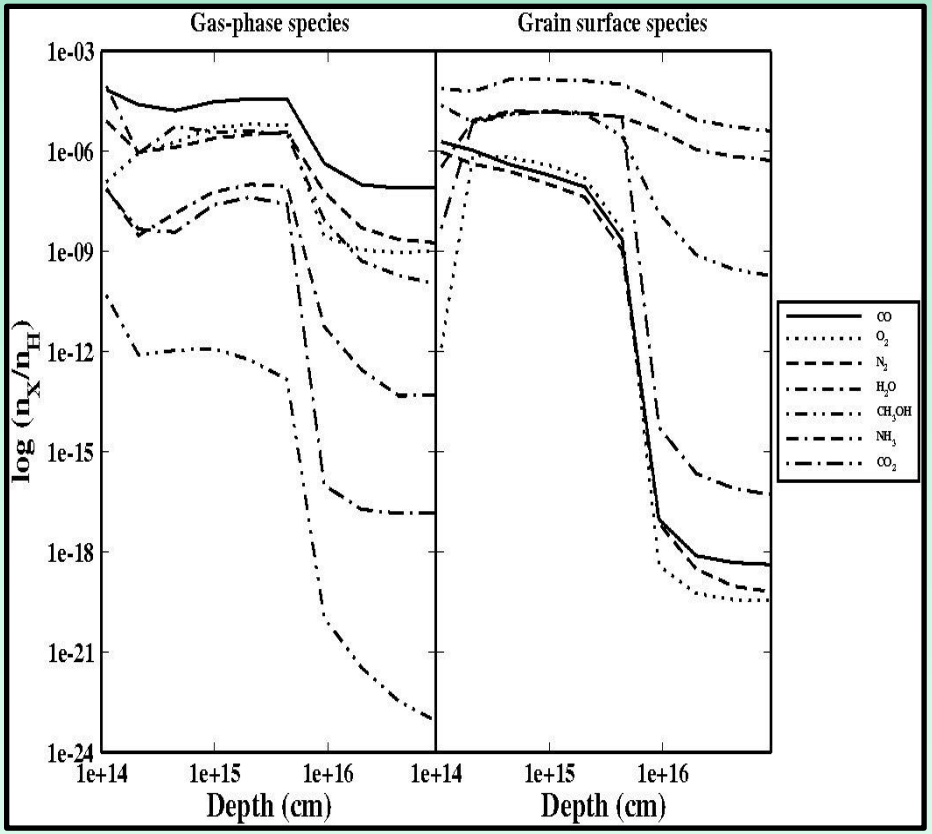


Figure 1 represents the time evolution of the density map of a collapsing cloud. As the time passes by, density of the cloud increases. We assume that there is a sink at deep inside the cloud. Sink is marked by the black box in the Fig.1. We assumed that any matter going inside the critical radius will contribute to the core mass. On the right panel a colour box is shown to have an idea about the evolution of density. Numbers on the right dictates the colour code of the density. Black means void or very low density region and yellow means very high density region. At the latter time, the contribution of yellow colour is very high at the inner region of the cloud which suggest that the density is increasing with time. It is clear from the figure that density is maximum just above the critical radius. From Fig. 2 it is clear that temperature increases as we enter deeper inside the cloud.

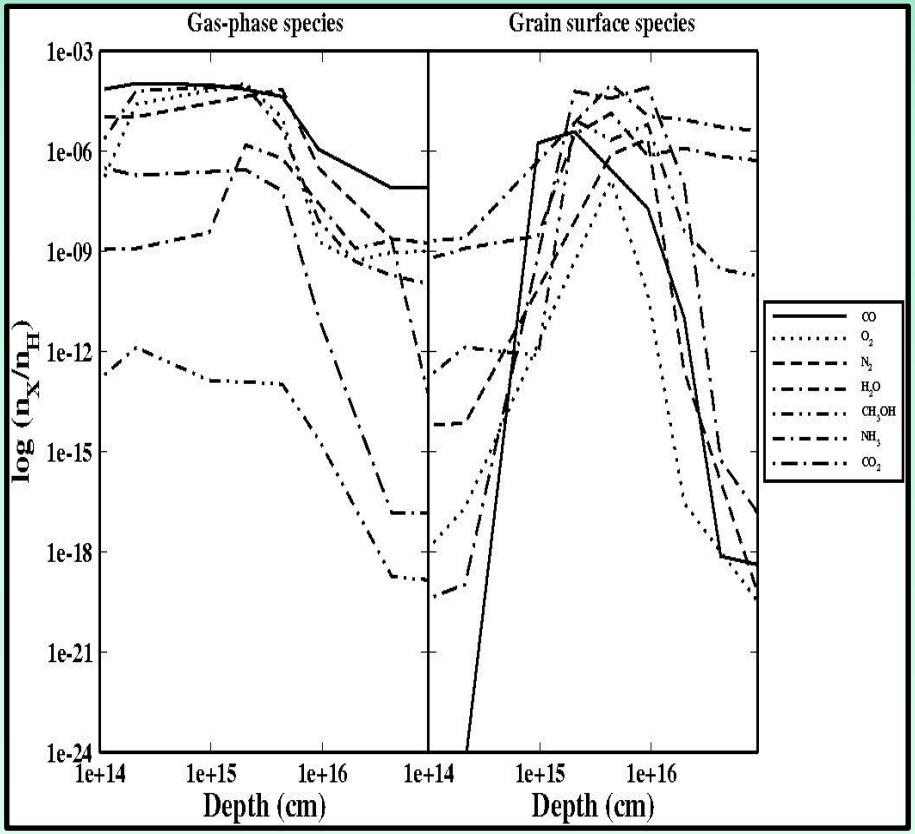
Coupled Hydro-chemical Model

Output of the hydrodynamic code is used as an input for the chemical code. We consider a reasonably large gas-grain chemical network into our consideration. Gas and grain are assumed to be coupled through the accretion and thermal evaporation process. Gas phase reactions are taken from the Woodall et al. (2007). We consider different neutral-neutral, radical-radical , and ion-molecular reaction pathways with the more realistic rate coefficients for the formation of different important interstellar bio-molecules from the Majumdar et al. 2011.

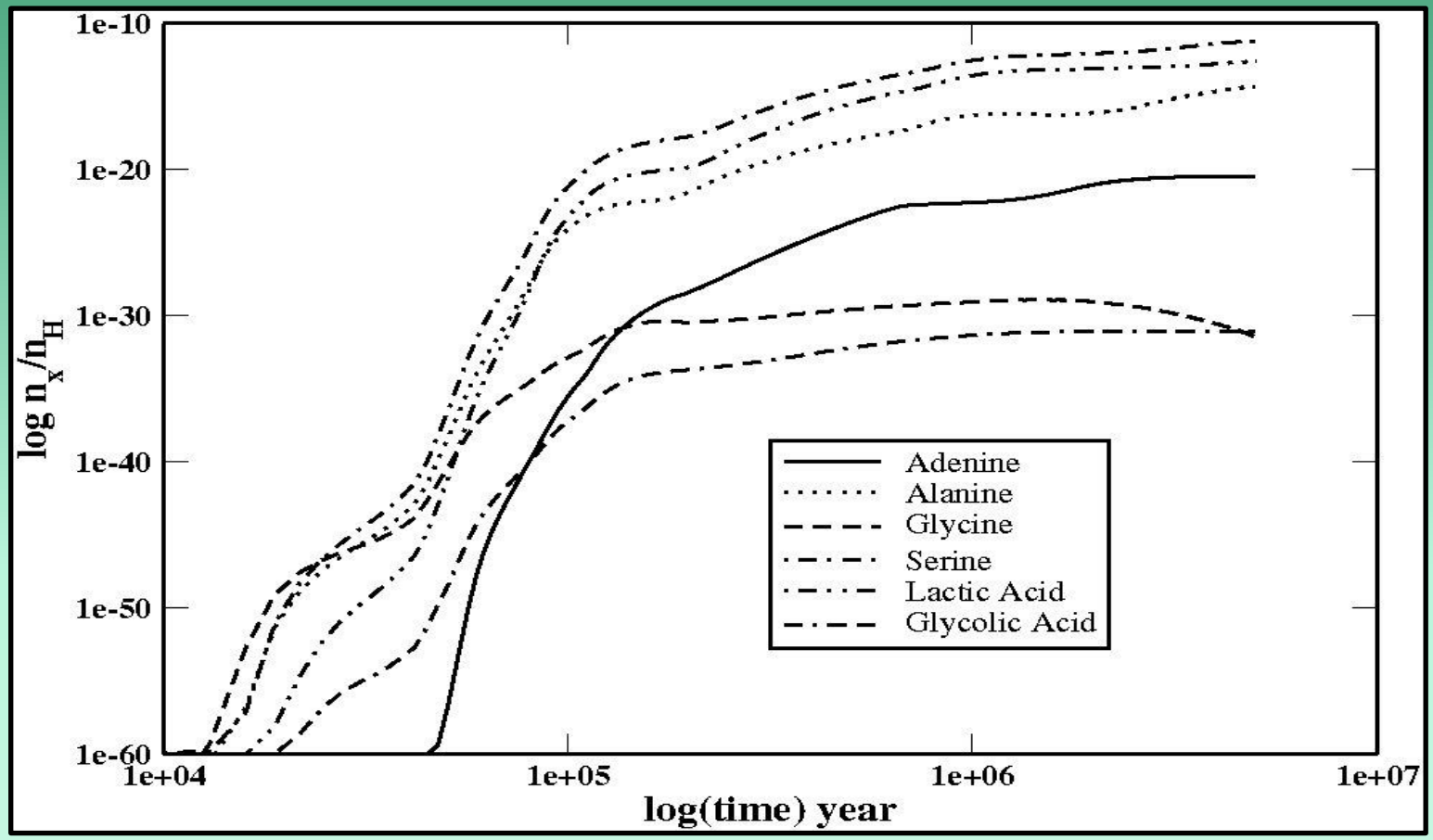
Depth dependence of abundance excluding the temperature dependence of the grain surface



Depth dependence of abundance including the temperature dependence of the grain surface



Time evolution of important bio-molecules



Here we explore the time evolution of various bio-molecules during the collapsing phase of proto-star. Bio-molecules are found to be more abundant by considering our present hydrodynamical model in compare to hydrodynamic model mentioned in Das et al. (2008a).

Conclusion

1. A TVD scheme is developed to study the dynamical properties of an interstellar collapsing cloud.

2. Large gas-grain network has been developed to follow the chemical evolution during the chemical processes.

3. Chemical evolution of various molecules are studied with some more important bio-molecules.

References

- Chakrabart, S , Chakrabarti, S.K., 2000, A & A, 354, L6
- Das, A, Chakrabarti, S.K., Acharyya, K, Chakrabarti, S, 2008, NEWAA, 13, 457
- Das, A, Majumdar, L, Chakrabarti, S.K., Chakrabarti, S, 2011 (submitted in MNRAS)
- Majumdar, L, Das, A, Chakrabarti, S.K., Chakrabarti, S, 2011 (submitted in APJ)
- Ryu, Dongshu, P, Jeremiah, Kang, H, Cen, R, 1993, APJ, 414:1-19
- Woodall, J., Agundez, M., Markwick-Kemper, A.J., Millar, T.J., 2000, A & A, 466, 1197