**INJECTION OF RADIOACTIVITIES INTO THE PROTOSOLAR CLOUD.** Harri A.T. Vanhala, Alan P. Boss, *Department of Terrestrial Magnetism, Carnegie Insitution of Washington, Washington DC 20015-1305, USA, harri@dtm.ciw.edu.*

According to the idea of the triggered origin of the solar system, the formation of our planetary system was initiated by an interstellar shock wave generated by a nearby explosive stellar event, such as a supernova explosion [1] or ejection of a planetary nebula from an asymptotic giant branch star [2]. In addition to triggering the collapse of the molecular cloud core, the shock wave also deposited fresh radioactivities into the precollapse core, giving rise to the anomalous abundances of extinct radionuclides measured in primitive meteorites [3].

The viability of the scenario must be verified through numerical simulations. There are three questions the simulations must answer: i) can the collapse of a molecular cloud core be induced by an impact of an interstellar shock wave? ii) can radioactivities carried by the shock wave be injected into the collapsing system? iii) is the time scale for the process sufficiently short for the survival of the radioactivities?

During the last few years, there have been several studies discussing assisted star formation (for a recent review see [4]) and its relation to the formation of the solar system (for reviews see [5][6]). Especially in the latter context, the problem has been examined by the two-dimensional piecewise-parabolic method (PPM) simulations of Foster and Boss [7][8][9] and the three-dimensional smoothed particle hydrodynamics (SPH) calculations of Vanhala and Cameron [5][10]. These studies concentrated on moderately slow (10-50 km/sec) shock waves impacting centrally condensed molecular cloud cores. Apart from the simulation methods themselves, the calculations also differed in their choice of thermodynamics: isothermal (PPM) vs. variable adiabatic index $\gamma$ (SPH).

The two sets of simulations agree on two of the three key issues mentioned above: molecular cloud cores can be triggered into collapse if the momentum of the shock wave is sufficiently high to compress the core significantly but not so large as to tear it apart. In terms of shock velocity, the benevolent range for assisted collapse is approximately 10-40 km/sec, depending on the evolutionary state of the pre-impact core [10]. The time scale for the collapse is $\sim 10^5$ years, well below the limits set by the survival of the radioactivities, even if the material were carried from a supernova explosion occurring at a distance of a few parsecs [5].

The principal unresolved difference between the two sets of simulations is the injection of radioactivities into the collapsing system. The PPM calculations have found that an appreciable amount of shock wave material, 10-20%, can be injected into the system through Rayleigh-Taylor-like fingers [8][9], while the SPH simulations did not detect any evidence for injection in the cases leading to collapse [5][10]. The main purpose of the current study is to address this basic difference between the results.

We used the 3D SPH code to study a problem similar to the standard case of Foster and Boss [7]. A spherically symmetric cloud was placed at the center of the three-dimensional coordinate system. The masses of the particles were varied in order to produce a configuration similar to the standard case of Foster and Boss: a marginally stable Bonnor-Ebert sphere joined smoothly to the surrounding medium. The cloud initially had a radius of 0.058 pc, temperature of 10 K, and central density of $\rho_c$ = 6.2 $\times$ $10^{-19}$ g cm$^{-3}$. The intercloud medium had $T_{\rm icm}$ = 10 K and $\rho_{\rm icm}$ = 7.3 $\times$ $10^{-22}$ g cm$^{-3}$. The shock wave was represented by a top-hat model, in which the edge of the wave (thickness 0.003 pc) was given the velocity $v_{\rm edge}$ = 20 km/sec, density $\rho_{\rm edge}$ = 7.3 $\times$ $10^{-20}$ g cm$^{-3}$ and temperature $T_{\rm edge}$ = 10 K, while the wind behind the leading edge had $\rho_{\rm wind}$ = 7.3 $\times$ $10^{-22}$ g cm$^{-3}$, $T_{\rm wind}$ = 10 K and $v_{\rm wind}$ = 0 km/sec. The simulation space extended to $r_{\rm xy}$ = 0.150 pc and -0.15 pc $< z <$ 0.15 pc, with the shock wave approaching from the $+z$ direction and starting at $z$ = 0.08. The boundary conditions were reflective on the cylindrical boundary and free inflow/outflow in the $z$ direction. In accordance with the calculations of Foster and Boss, the value of the adiabatic index was kept constant at $\gamma$ = 1.00001, instead of using the equation of state solver with a variable adiabatic index.

Figures 1-2 show the results from our calculation run with 16,947 particles. Due to slightly higher densities in the shock wave and the intercloud medium, the SPH calculation proceeds somewhat faster than the Foster and Boss standard case, but the basic result is the same. Both calculations lead to the collapse of the core after the leading edge of the shock wave has passed. The post-shock material, which initially was at rest, has not moved appreciably during the simulation. On the other hand, some of the shock wave material has penetrated the core in finger-like structures (Fig. 1) and is mixed with the collapsing cloud (Fig. 2). The injection efficiency, defined as the amount of material retained in the collapsing area compared with the amount originally incident on the core, is 19% in our 3D SPH calculations, remarkably close to the 16% of the 2D PPM calculations of Foster and Boss [8].

The reason why we are now able to detect injection of shock wave material into the collapsing core using the SPH code lies in the thermodynamics: in the current calculations we chose a constant value $\gamma$ = 1.00001 for the adiabatic index instead of employing the variable $\gamma$ scheme. The choice of thermodynamics, previously found to be important in determining whether the impacted core will collapse [5][7][10], is now found to play a crucial role in determining whether mixing of material between the shock flow and the core occurs. If the temperature of the post-shock gas is sufficiently high to lower the value of the adiabatic index $\gamma$ close to 1 but the cloud gas is cold ($\gamma = 5/3$), mixing does not occur. On the other hand, if the temperature in the post-shock gas remains low, mixing can occur. However, in the calculations using a variable $\gamma$, collapse will then not take place because $\gamma >$ 4/3 [10]. If an isothermal equation of state is used, as in the calculations described here and in the calculations of Foster and Boss [7][8][9], collapse occurs with the mixed material trapped in.

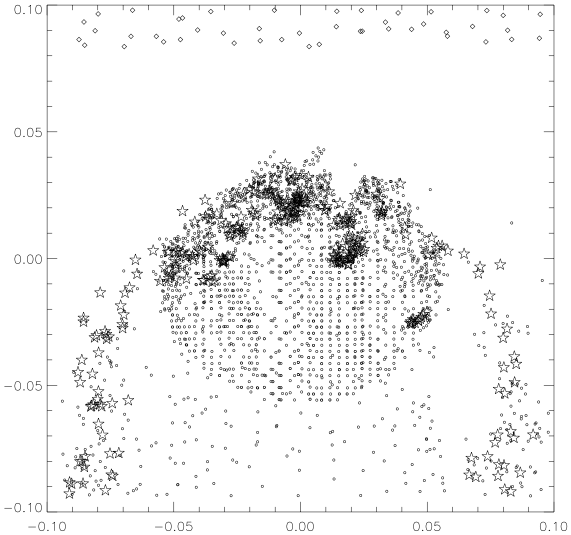

Figure 1. Particle positions in a simulation run with a total of 16,947 particles (11,506 in the core and cloud, 5441 in the shock) at $t$ = 12,072 yr. The core material is denoted by small circles, the shock flow material by stars and the post-shock flow particles by small diamonds. The system is shown in the $xz$ plane, with the units in parsecs. The initial shock velocity is 20 km/sec in the shock edge and 0 km/sec in the post-shock flow. The shock front material is penetrating the facing side of the core in curving finger-like structures.

Our results stress the need for a better understanding of the thermodynamics and especially the state of hydrogen in interstellar space. In our variable $\gamma$ calculations we have assumed an equilibrium mix between the ortho and para states of hydrogen [5]. However, transformation between ortho- and parahydrogen is a complicated process and is not well studied in interstellar conditions. By largely determining the value of $\gamma$ at low temperatures, the state of hydrogen influences both the stability of a molecular cloud core and the conditions under which material can be mixed into the collapsing system.

If our assumption of an equilibrium mix between the two states of hydrogen is valid, there are a few possibilities for mixing material into the collapsing core even if the equation of state with a variable $\gamma$ is used. When the core is pushed to the point of collapse, its temperature rises so that the $\gamma$ falls below 4/3. It is possible that the hot post-shock gas is able to penetrate into the collapsing system at the later stages of the collapse not followed in the SPH simulations.

It is also possible that cooling behind the shock front is more efficient than what is assumed here. In this case the core is pushed to collapse by the hot shock front gas, and the cooler post-shock flow material may be injected later into the collapsing core. This possibility can be examined by a more detailed examination of the shock structure and is planned for a future study.

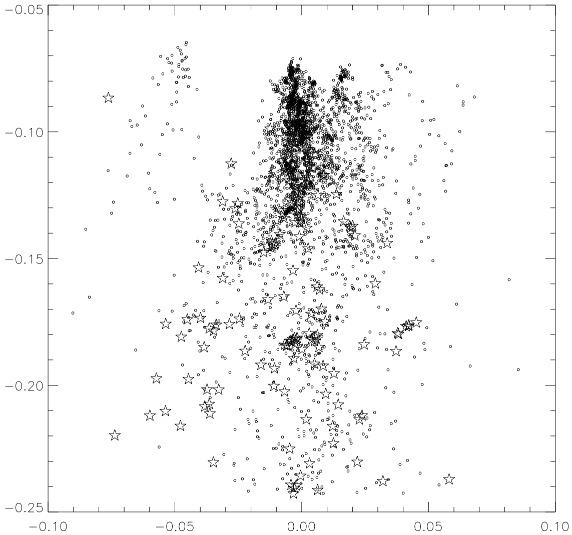

Figure 2. Same as Fig. 1 but at $t$ = 235,409 yr. The core density has increased to $1.9 \times 10^{-11}$ g cm$^{-3}$, or $3 \times 10^{7}$ times the original peak density. The amount of shock wave material mixed with the core is 19 % of the material originally incident on it.

The injection between the hot shocked material and the cold molecular cloud gas can also occur through small-scale instabilities that our calculations do not resolve [5]. The reason that these instabilities are not observed in the 2D PPM calculations is that in the isothermal case mixing on the larger scales dominates. This effect could be studied through PPM calculations where the value of the adiabatic index $\gamma$ is different in the shock wave and in the molecular cloud gas.

In summary, our 3D SPH calculations have found that material can be mixed into a collapsing molecular cloud core. Whether injection occurs depends on the thermodynamics employed in the calculations. Further work is required to understand the injection process in detail and to determine under what conditions mixing can occur.

**References:** [1] A.G.W. Cameron et al. (1995) *Ap.J.Lett.* **447**, L53-L57; [2] G.J. Wasserburg et al. (1994) *Ap.J.* **424**, 412-428; [3] T. Lee et al. (1976) *Geophys.Res.Lett.* **3**, 41-44; [4] B.G. Elmegreen (1998) in *Origins of Galaxies, Stars, Planets and Life*, eds. C.E.Woodward, H.A.Thronson and M.Shull (Astr.Soc.Pacific), in press; [5] A.G.W. Cameron et al. (1997) in *The Astrophysical Implications of the Laboratory Study of Presolar Materials*, eds. T.J.Bernatowicz and E.Zinner (Woodbury NY: AIP), pp. 665-693; [6] A.P. Boss and P.N. Foster (1997) in *The Astrophysical Implications of the Laboratory Study of Presolar Materials*, eds. T.J.Bernatowicz and E.Zinner (Woodbury NY: AIP), pp. 649-664; [7] P.N. Foster and A.P. Boss (1996) *Ap.J.* **468**, 784-796; [8] P.N. Foster and A.P. Boss (1997) *Ap.J.* **489**, 346-357; [9] A.P. Boss and P.N. Foster (1997) *Ap.J.Lett.*, in press; [10] H.A.T. Vanhala and A.G.W. Cameron (1998) in preparation.