INJECTION OF SHORT-LIVED RADIOACTIVITIES INTO THE FORMING SOLAR SYSTEM. H.A.T. Vanhala, Universities Space Research Association, Washington, DC 20036, USA, (hvanhala@usra.edu).

Studies of primitive meteoritic material have revealed the presence of short-lived radioactivities in the early Solar System [1]. These radioactivities include $^{24}$Ca (half-life 0.1 Myr), $^{30}$Cl (0.3 Myr), $^{26}$Al (0.7 Myr), $^{10}$Be (1.5 Myr), $^{60}$Fe (1.5 Myr), $^{50}$Mn (3.7 Myr), $^{107}$Pd (6.5 Myr), $^{182}$Hf (9 Myr), $^{129}$I (15.7 Myr), and $^{244}$Pu (82 Myr). The longer-lived isotopes may represent the ambient inventory of the local interstellar medium, but the presence of the shortest-lived radionuclides (half-life less than a few million years) requires their introduction into the Solar System shortly before their inclusion into the meteoritic material. The short half-lives of the radionuclides set a strict time limit of no more than about 1 Myr between their production and their incorporation into the meteorite inclusions in the early Solar System [1].

This timescale seems to be at odds with the standard model for the formation of low-mass stars [2], which suggests that Sun-like stars form when dense molecular cloud cores evolve through ambipolar diffusion to gravitational collapse on a timescale of $\sim$10 Myr [3]. If the short-lived radioactivities present in the early Solar System were produced through stellar nucleosynthesis, the leading explanation for their origin, and mixed into ambient interstellar material, the shortest-lived of the radioactivities would have decayed away during the $>10$ Myr time of the molecular cloud evolution.

The apparent discrepancy could be resolved if the radioactivities were produced locally in the solar nebula or in the parent molecular cloud. Several scenarios based on this philosophy have been suggested [1], recently in the form of radionuclide production by energetic particles emanating from protostellar flares in the early Solar System [4]. While the scenario can explain the presence of some radioactivities, it has severe difficulties explaining the observed properties of others and cannot account at all for several detected radioactivities [5]. These results suggest that while some of the radioactivities could have been produced locally, several of them must have been produced through stellar nucleosynthesis.

While there are several possible stellar sources of short-lived radioactivities [1], the favored explanation is a supernova explosion occurring near the site where the Solar System was formed. The best way to connect a supernova with the formation of the Solar System is through the hypothesis of the triggered origin of the Solar System [6]. According to this scenario, short-lived radioactivities were produced in a supernova and then carried to the molecular cloud core from which the Solar System was formed by a shock wave propagating from the supernova explosion. In addition to injecting the freshly synthesized radioactivities into the core, the shock wave also triggered the collapse of the core. A variation on this theme — the possibility that the supernova explosion occurred after the collapse of the presolar cloud, during the early phases of Solar System evolution — has been proposed recently [7], but it remains unclear whether this variation is viable due to timing and energetics questions. As a result, the triggered origin scenario remains the mostly likely explanation for the presence of the short-lived radioactivities in the early Solar System.

The viability of the triggered origin scenario can be investigated through multidimensional hydrodynamic simulations studying the interaction between interstellar shock waves and molecular clouds. A variety of simulation methods have been used in the last few years to investigate the viability of the hypothesis (see [8] and references therein). The simulations have shown that molecular cloud cores can be triggered into collapse by moderately slow ($\leq45$ km s$^{-1}$) shock waves, and the time scale of the process, $<10^3$ years, is sufficiently short for the radioactivities to have survived in the detected amounts. Figure 1 shows a series of snapshots from a sample three-dimensional smoothed particle hydrodynamics simulation.

Two-dimensional piecewise-parabolic method calculations have been used to investigate the process of the injection of shock wave material into the collapsing system (see [8] and references therein). While the central parts of the core are being pushed to collapse, material carried by the shock wave collects into clumps on the surface of the core. The situation — dense clumps of material on top of the less dense outer parts of a self-gravitating molecular cloud core — leads to the development of Rayleigh-Taylor type instabilities, as shown in Fig. 2. By the end of the calculation, approximately 10% of the shock wave material originally present on the core has been injected into the inner regions of the system. Details of these calculations suggest that the existence of temporal and spatial heterogeneities in the abundances of short-lives radioactivities in the early Solar System is possible [9].

These calculations, performed using two different simulation methods, show that the hypothesis of the triggered origin of the Solar System is viable. The calculations indicate that the shock wave transporting material from a nearby stellar nucleosynthesis site could have triggered the formation of the Solar System, and that some of the material carried by the shock wave could have been injected into the forming Solar System. The record of this process was then preserved in primitive meteoritic material.

Figure 1: Interaction between an interstellar shock wave and a molecular cloud core in a three-dimensional smoothed particle hydrodynamics simulation. The shock approaches from the $+z$ direction with a velocity $25 \text{ km s}^{-1}$. The system is shown in the $(x, z)$-plane with the units in parsecs. The system is shown at $t = 21,000 \text{ yr}$ (top panel), $27,000 \text{ yr}$ (second panel), $42,000 \text{ yr}$ (third panel), and $70,000 \text{ yr}$ (bottom panel) after the initial approach of the shock wave. The grayscale contours show the density in the system and range from $1.0 \times 10^{-21} \text{ g cm}^{-3}$ (light) to $1.0 \times 10^{-14} \text{ g cm}^{-3}$ (dark). During the interaction, the core is stretched to a thin filament, the head of which is pushed into collapse (last panel).

Figure 2: Injection of shock wave material through Rayleigh-Taylor instabilities developing on the surface of the compressed molecular cloud core, as revealed by a two-dimensional piecewise-parabolic method simulation. The system is shown at $t = 88,000 \text{ yr}$ (top panel), $110,000 \text{ yr}$ (second panel), $132,000 \text{ yr}$ (third panel), and $142,000 \text{ yr}$ (bottom panel) after the initial approach of the shock wave. The grayscale and black-line contours depict the gas density in the system and range from $6.2 \times 10^{-21} \text{ g cm}^{-3}$ to $7.9 \times 10^{-16} \text{ g cm}^{-3}$. The white contours show the behavior the shock wave material.