Abundance of Iron-60 in Molecular Clouds

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Introduction: Understanding the birthplace of the Sun is of fundamental importance when trying to understand the origins and the formation history of the Solar System. The isotope ^{60}Fe, present in the early solar system at levels of ^{60}Fe/^{56}Fe $\sim$ a few $\times 10^{-7}$ [1-4], provides us with a strong constraint that leads us towards this location. Due to its short half-life (recently revised at 2.6 Myr [5]), this short-lived radionuclide (SLR) could not have been inherited from the interstellar medium (ISM) in such high abundance if we consider the traditional models where the ^{60}Fe is injected in the warm phase of the ISM and cools over $\sim$ 100 Myr before forming molecular clouds [6,7]. Further more, this neutron rich isotope could not have been produced by spallation reaction within the early solar system [8]. One on several external nucleosynthetic source is hence required to explain the once-presence of this SLR. Although AGB stars have been suggested as a source of ^{60}Fe [9], they are not naturally associated with star forming regions [10]. The core-collapse supernova is the only plausible source of this element [11].

Many scenarios attempt to explain how the Solar System inherited its ^{60}Fe and other SLRs from a supernova. The "Supernova Trigger" model suggests the Solar system inherited its SLRs as a supernova shock provoked the collapse of a stellar core [12,13]. However, for the supernova shock to simply collapse the stellar core and not destroy it, it must have slowed to a few $\times 10$ km s^{-1} [14]. This requires a very specific molecular cloud geometry, and it makes the probability of this scenario hard to assess. The "Aerogel" model suggest the supernova injected the SLRs into an already formed disk a fraction of a parsec away [11,15]. However, the likelihood of this scenario occurring has been calculated at around 1 % [16,17]. Here we suggest a different model.

Cloud Enrichment Model: A common point in the scenarios described in the previous section is that ^{60}Fe is injected in an already formed structure, whether it be a core or a disk. This was thought necessary as the half-life of ^{60}Fe is much shorter than the time it takes to form a molecular cloud to form and collapse. However, recent work has shown that it is possible to rapidly form molecular clouds using turbulent convergent flows, as fast as 10-20 Myr [18,19]. We hence suggest a model where the formation of a molecular cloud is triggered by the shocks of supernovae from a nearby star-forming region. In this model, dubbed "SPACE" (Supernova Propagation And Cloud Enrichement), the ^{60}Fe is delivered while the molecular cloud is being built by the supernova shock triggering its formation [20]. Another possible scenario, similar to the previous one, would involve supernova in a massive star forming region contaminating part of an already formed molecular cloud with ^{60}Fe and other SLRs, possibly accelerating the collapse of a less dense region in the cloud and triggering an episode of star formation [20].

Computer Simulations of Model: To explore this scenario, we are performing simulations using RAMSES, a 3D-MHD code [21]. This code solves the MHD equations using Godunov-type methods. It includes self-gravity and cooling, which has been slightly modified to account for the high energies involved in supernova explosions, following the cooling coefficients obtained from Sutherland and Dopita [22]. To simulate a supernova, we add the appropriate mass and 10^{51} ergs of energy in a radius of a few parsecs. This gas expands rapidly and appropriately simulates the Sedov and the snowplow phases of a supernova [23]. In addition, tracer particles have been added to follow the supernova ejecta and, by extension, the location of ^{60}Fe. These tracers can either simulate gas particles, or dust particles entrained in the gas. Finally, the code was modified to allow us to simulate many supernovae staggered in time. Hence, at times defined by the user, the code is able to add the appropriate mass and energy at a pre-determined position to simulate a supernova.

This modified code will be used to simulate the cloud enrichment model. Computer simulations will show if supernova shockwaves can cause the rapid collapse of a molecular cloud in a way similar to turbulent convergent flows. Mixing between the interstellar medium and the supernovae ejecta will be followed to assess the amount ^{60}Fe injected in the condensing molecular cloud.

Figure 1 shows preliminary results of these simulations. Two supernovae have exploded 0.1 Myr apart. Together, these supernova have snowplowed $\sim 3000\,M_\odot$ of material. Figure 2 shows

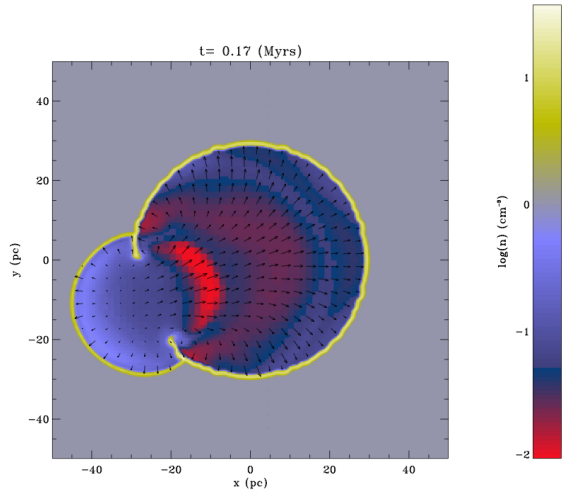

Figure 1: Density of the gas in cm^{-3}, .17 Myr after the explosion of the first supernova

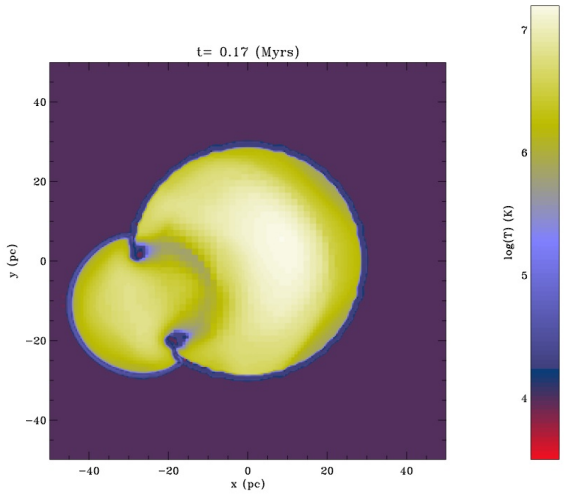

Figure 2: Tempersture ofthe gas in K, .17 Myr after the explosion of the first supernova. Cold clumps can be seen where the ejecta of the first and second supernova collide

the temperature of the gas. At the edge of the supernova, the gas cools rapidly. Some dense clumps where the ejecta from the supernovae collide have cooled to a few $\times$ 100 K, cooler than the surrounding ISM. In a more realistic scenario with more supernovas staggered through a longer period of time, It is not unreasonble to expect clums of a few 100s of $M_\odot$ to cool, condense and form small molecular cloud, enriched in ^{60}Fe and other SLRs. Results of a more detailed, more physically realistic simulation will be discussed at the conference.

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