ENHANCED ABUNDANCE OF 26AL AND 60FE IN GIANT MOLECULAR CLOUDS.
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Introduction: The presence and initial abundances of short-lived radionuclides (SLRs; e.g., ^{26}Al, ^{41}Ca, ^{53}Mn, ^{60}Fe, ^{182}Hf) in the solar system are widely used to understand the timescales of processes in the early solar system and the environment where our Sun formed [1,2]. These SLRs are believed to have a stellar origin and have either been inherited from the interstellar medium or injected into the protosolar molecular cloud core prior to or contemporaneously with its collapse [3]. A better understanding of the abundance and distribution of the ^{26}Al and ^{60}Fe SLRs in star-forming regions may allow us to probe the astrophysical environment of solar system formation.

In massive stars ^{26}Al is produced by hydrostatic and explosive nucleosynthesis and is ejected into the interstellar medium by both stellar winds and explosions in different proportions, depending on the initial mass of the star, while ^{60}Fe is essentially only ejected during supernova events [4]. Recent high-precision measurements of the daughter product of ^{26}Al (^{26}Mg*) in meteorites and their components suggest that despite its short-half life of 0.73 Myr, ^{26}Al was present at levels of ^{26}Al/^{27}Al ~2.8 10^{-5} at the birth of the solar system [5]. Although the initial solar system abundance of the ^{60}Fe nuclide ($t_{1/2}$~2.6 Myr) is still controversial, recent studies, which yield an initial ^{60}Fe/^{56}Fe value of $<10^{-8}$ in differentiated meteorites [6-7], indicate a very low initial solar system ratio of ^{60}Fe/^{26}Al < 0.006, much lower than the average galactic ^{60}Fe/^{26}Al ratio of about 0.5 inferred from γ–ray astronomy [8].

To understand the astrophysical significance of the apparent mismatch between the galactic and solar system ^{60}Fe/^{26}Al ratios, we have been running numerical simulations of Giant Molecular Clouds (GMCs) where stellar birth, death and rebirth takes place, and where we have been tracking the production, distribution and admixing of ^{26}Al and ^{60}Fe in the evolving GMCs.

Method: We use a numerical 3D model of the magnetodhyrodynamics of GMCs to study the injection and transport of ^{26}Al and ^{60}Fe, following the fate of these SLRs from ejection via the supernova and stellar wind mechanisms to their incorporation into newly formed stars. The MHD and self-gravity model includes a standard optically thin cooling function and heating by UV-photons, which is quenched in dense gas, leading to the collapse and formation of molecular clouds (MCs). The simulation box is a 40 to 80 pc cube, filled with gas of an average mass density between 10^{-22} and $5{\cdot}10^{-23}$ g cm^{-3}, for a total mass of 10^5 to $4{\cdot}10^5$ solar masses, with 0.2–0.4 pc resolution. The gas in the GMC initially has velocity dispersions in accord with Larson's velocity size scaling [9], arising from an external driving force representing kinetic energy cascading from scales larger than the box. After a few million years rapidly cooling gas forms molecular clouds (MCs), in which star formation is treated with a star formation recipe, with stellar masses drawn from an Initial Mass Function (IMF) model [10]. A database of supernova yields [4], stellar life times, mass losses, and wind speeds [11] is used to keep track of the stars and their contributions of SLRs back into the GMC gas reservoir. The abundance of SLRs is followed by using a passive scalar equation, with identical runs, differing only in the half-lives and yield tables used to follow ^{26}Al and ^{60}Fe, respectively.

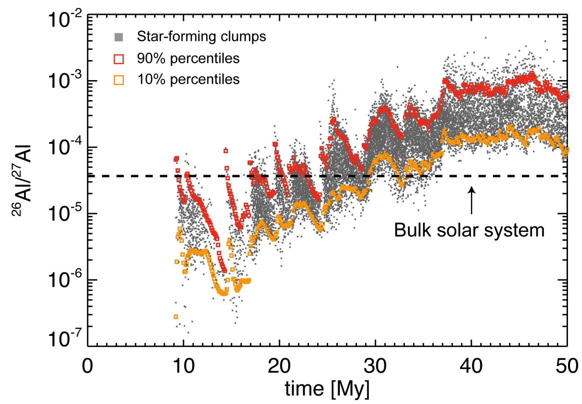

Figure 1: Concentration of ^{26}Al in the star-forming gas of an evolving 10^5 solar mass GMC.

Results: The first important observation emerging from our simulations is that the concentration of ^{26}Al in the star-forming gas is frequently similar to, or higher than, the ^{26}Al/^{27}Al value of ~2.8 10^{-5} inferred to have been present in the nascent solar system ([5] Fig. 1). Moreover, there is a significant variability in the ^{26}Al/^{27}Al ratios amongst the individual star-forming clumps throughout the evolution of the GMC. We note that the ^{26}Al/^{27}Al are steadily increasing throughout the evolution of the GMC, and that already about 20 Myr after the first SNe exploded, all star-forming regions have ^{26}Al/^{27}Al ratios comparable to or larger than that inferred for the solar system. Therefore, the concentration of ^{26}Al in star-forming regions inferred from our simulations supports the idea that the occurrence of ^{26}Al in the early solar system represents a generic feature of the chemical evolution of GMCs.

Figure 2 shows the ratio of ^{60}Fe to ^{26}Al in star forming gas and individual SNe ejecta, and also the ratio of accumulated yields at any one time. The latter is a direct estimate of the ratio of the expected gamma-ray fluxes, since the large majority of ejected SLR nuclei will have had time to decay. The ratio of the average interstellar medium abundances at any one time is larger than this ratio by the ratio of life times (3.6). The ratio in star forming gas is still larger, reflecting that the average time from SN ejection to inclusion in star formation is of the order of 3 Myr in these simulations.

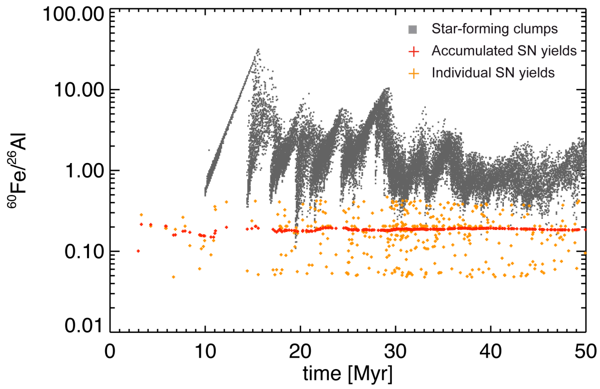

Figure 2: Ratios of ^{60}Fe to ^{26}Al in the star-forming gas of an evolving GMC.

The predicted ratio of ^{60}Fe to ^{26}Al gamma ray flux is slightly less than 0.2, which is consistent with the observed value, 0.148 ± 0.06 [8]. The agreement is expected, since we are using yields [4] whose interstellar medium averaged value is consistent with [8]. The ratio in star-forming gas is consistent with an average transport time from SNe of about 3 Myr, leading to a ^{60}Fe/^{26}Al ratio in star-forming gas of the order of unity; very far from the value 0.006 mentioned in the Introduction. Thus, there is no plausible modification on the supernovae and stellar winds yields that can locally simultaneously give the observed levels of ^{26}Al/^{27}Al and the very low levels of ^{60}Fe/^{56}Fe inferred from meteorites [6, 7]. The result is very robust and model independent, in that the average galactic ratio ^{60}Fe/^{26}Al is well constrained by gamma-ray observations [8].

Discussion: We consider three possibilities to account for the mismatch between the solar system's low initial ^{60}Fe abundance compared to that predicted from our numerical simulation: (*i*) uncertainties in the ^{60}Fe supernova yields, (*ii*) contamination of the protosolar molecular cloud from ^{26}Al-rich winds of massive star and, (*iii*) the solar system's initial ^{60}Fe/^{56}Fe value inferred from meteorites is not representative of the initial solar system's bulk ^{60}Fe abundance.

The ^{60}Fe/^{26}Al ratio of accumulated supernovae yields during the evolution of the simulated GMC is in keeping with the observed galactic ^{60}Fe/^{26}Al ratio inferred from γ–ray astronomy [8]. This observation rules out significant uncertainties in the supernova yields to account for the apparent low ^{60}Fe/^{26}Al ratio inferred for the nascent solar system.

Contamination of the nascent solar system from a the winds of a massive star could, in principle, result in the apparent low ^{60}Fe/^{26}Al inferred from meteorite studies. However, the space-time window for contamination of a solar system forming region with a low ^{60}Fe/^{26}Al ratio is extremely small, requiring such a system to form in the immediate neighborhood of a rare, very massive star, just before the end of its very brief lifetime. Moreover, it requires that the wind ejecta mix with an essentially ^{60}Fe free gas, which nevertheless has an ^{26}Al/^{27}Al ratio consistent with the initial solar system value. Although this scenario cannot be ruled out it is statistically very improbable.

Alternatively, the low initial solar system abundance of ^{60}Fe/^{56}Fe inferred from Ni-isotope measurements of differentiated meteorites [6, 7] may not be representative of the average initial abundance of ^{60}Fe in the solar system. Larsen et al. [5] recently proposed that large-scale heterogeneity in the initial abundance of ^{26}Al may have existed throughout the inner solar system, with possibly up to 80% reduction relative to the ^{26}Al/^{27}Al ratio present in the solar system oldest solids, calcium-aluminum-rich inclusions (CAIs). The ^{26}Al heterogeneity amongst inner solar system objects have been ascribed to thermal processing of molecular cloud material, which resulted in preferential loss by sublimation of a thermally unstable ^{26}Al-rich carrier, producing residual isotopic heterogeneity. In this view, CAIs represent samples of the complementary gaseous reservoir enriched in ^{26}Al by thermal processing, which resulted in the widespread ^{26}Al depletions observed among the inner solar system bodies. If the ^{60}Fe carrier phase was appreciably more labile than the ^{26}Al carrier, than thermal processing would have effectively remove most of the ^{60}Fe from the inner solar system solids thereby significantly enhancing the ^{60}Fe concentration of the gas phase. If this interpretation is correct, we predict that samples of the gas phase such as CAIs will define internal isochrone relationships suggesting initial ^{60}Fe/^{56}Fe ratios $>>1\times10^{-6}$.

References: [1] McKeegan, K. D. & Davis, A. M (2003) Treatise on Geochemistry, Vol. 1, 431 [2] Goswami, J. N. (2004) New Astron. Rev. 48, 125 [3] Sahijpal, S. & Goswami, J. N. 1998, ApJ, 509, L137 [4] Limongi, M. & Chieffi, A. (2006) *ApJ 647,* 483 [5] Larsen K. et al. (2011) *ApJ, 753,* L37 [6] Tang, H. & Dauphas, N. (2011) 42nd LPSC # 2068 [7] Spivak-Birndorf, L. et al. (2011) 42nd LPSC # 2281 [8] Wang, N. et al (2007) A&A 469, 1005 [9] Larson, R. B. (1981), RASMN 194, 809 [10] Nordlund, Å. & Padoan, P. (2002) ApJ 576, 870. [11] Lopez-Merino, A (2006) PhD Thesis, Univ. of Copenhagen.