SHORT-LIVED RADIONUCLIDES IN THE EARLY SOLAR SYSTEM TRACE SEQUENTIAL STAR FORMATION . M. Gounelle[1] and G. Meynet[,3], [1]LMCM, UMR 7202, CNRS & MNHN, CP52, 57 rue Cuvier, 75005 Paris, France. (gounelle@mnhn.fr) [2]Geneva Observatory, Geneva University, 1290 Sauverny, Switzerland.

Short-lived radionuclides (SLRs) are radioactive elements ($T_{1/2}$ < 200 Myr) which were present in the nascent solar system and are now extinct [1]. While the abundance of SLRs with the longest half-lives ($T_{1/2}$ > 3 Myr) is compatible with the expectations of Galactic evolution models [2, 3], others have a last-minute origin. ^{7}Be, ^{10}Be, ^{36}Cl and ^{41}Ca probably originated within the protoplanetary disk from the irradiation of gas and dust by energetic particles accelerated by the protoSun [4-6]. On the other hand, ^{26}Al and ^{60}Fe were probably synthesized by massive stars and added to interstellar gas which will eventually make up the bulk of our solar system [7]. Identifying the detailed mechanisms of ^{26}Al and ^{60}Fe production and mixing will shed a light on the relationship between the Sun formation history and massive stars.

Since 1977, the dominant model is that of a single supernova (single-SN) injecting ^{26}Al and ^{60}Fe either in the prestellar core [8, 9] or in the already formed disk [10].The single-SN scenario is now considered less likely because injection of a SN ejecta in a dense prestellar core (n_{H2} ~10^5 cm^{-3}) is not effcient enough to account for the abundance of ^{26}Al and ^{60}Fe [9]. In the second scenario, which has been receiving a lot of attention the last years [11-13], the SN has to be very close (< 0.3 pc) to the protoplanetary disk in order to allow the disk to intercept enough ejecta to account for the solar system abundance of ^{26}Al and ^{60}Fe. It is thus assumed that the massive star, which evolved into a SN, and the protoplanetary disk were coeval, and formed in the same stellar cluster [14]. This configuration ise extremely unlikely, mainly because the evolution timescale of massive stars is too long compared to protoplanetary disks photo-evaporation timescales in the vicinity of a massive star [15 , 16]. In addition, none of these models can reproduce the observed solar system abundance of ^{26}Al and ^{60}Fe since SNe yields are systematically depleted in ^{26}Al relative to ^{60}Fe and their respective initial abundances [17, 18]. Finally, injection into a disk would introduce a shift in the oxygen isotopic composition of the disk relative to that of the Sun [19], which is not observed [20].

In a recent work, we proposed that ^{60}Fe was incorporated in the forming solar molecular cloud from a few supernovae belonging to a previous generation of stars [7]. In such a model, the presence of ^{60}Fe is a necessary output of star formation mechanisms as the second generation molecular cloud (that of the solar system formation) is built by the shockwaves of the same SNe whose ejecta deliver ^{60}Fe. Though not calculated, injection efficiency should be significantly higher than in the single-SN model as it occurs in a phase of low density (n_{H2} ~10 cm^{-3}), more penetrable by SN ejecta than dense phases such as a disk (which is seen by the ejecta as an impassable wall).

Recent measurements strengthen our model. Taking into account the longer half-life of ^{60}Fe (2.6 Myr vs. 1.5 Myr, [21]) will increase the abundance of ^{60}Fe produced by the first generation of stars and release the constraint (already loose) on the mixing effciency. Considering the possible low initial abundance of ^{60}Fe [22] would have the same effect. The SPACE (Supernova Propagation And Cloud Enrichment) model cannot however account for the presence of ^{26}Al in the early solar system as this SLR is not produced effciently enough (relative to ^{60}Fe) by SNe.

A potential solution might be that ^{26}Al is delivered by massive star winds rather by SN ejecta. This proposal was made before, including by us [23] and others [24, 25]. However [25] did not pay much attention to the detailed astrophysical setting, while [24] invoked a runaway Wolf-Rayet star which is a very unlikely event.

We will propose a solution which would be in line with the sequential star formation scheme evoked for ^{60}Fe, though operating on a smaller scale. The scenario to be explored is the delivery of wind-produced ^{26}Al into a dense shell around a massive star from the second generation. Our solar system would form through gravitational instabilities in that dense shell following recently summarized mechanisms [26]. It will contain ^{60}Fe from the first generation of stars and ^{26}Al from a single star wind of the second generation. Because ^{60}Fe is not produced by winds, both SLRs are truly decoupled. It is important to note that the physical mechanism retained for ^{26}Al (injection from a hot phase into a cold phase) is the same as for ^{60}Fe (and as for SLRs accounted for by Galactic background models). It would mean there exists a satisfying generic and unique mechanism which explains the presence of all SLRs (of stellar origin) in the solar system. That mechanism would operate at large scales for SLRs with long half-lives and at small scales for SLRs with short half-lives. This overall model for the origin of SLRs is in line with astronomical observations of sequential star formation [27, 28].

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