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The abundance of ^{26}Al-rich planetary systems in the Galaxy

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ABSTRACT

One of the most puzzling properties of the solar system is the high abundance at its birth of ^{26}Al, a short-lived radionuclide with a mean life of 1 Myr. Now decayed, it has left its imprint in primitive meteoritic solids. The origin of ^{26}Al in the early solar system has been debated for decades and strongly constrains the astrophysical context of the Sun and planets formation. We show that, according to the present understanding of star-formation mechanisms, it is very unlikely that a nearby supernova has delivered ^{26}Al into the nascent solar system. A more promising model is the one whereby the Sun formed in a wind-enriched, ^{26}Al-rich dense shell surrounding a massive star ($M > 32\ M_{\odot}$). We calculate that the probability of any given star in the Galaxy being born in such a setting, corresponding to a well-known mode of star formation, is of the order of 1%. It means that our solar system, though not the rule, is relatively common and that many exo-planetary systems in the Galaxy might exhibit comparable enrichments in ^{26}Al. Such enrichments played an important role in the early evolution of planets because ^{26}Al is the main heat source for planetary embryos.

Key words. meteorites, meteors, meteoroids – stars: formation – stars: protostars – planetary systems

1. Introduction

While more and more planetary systems are being discovered around Sun-like stars (Quintana et al. 2014), it is important to know how common the properties of the solar system are, as well as what the exact circumstances of its birth are in a star-forming region.

One of the most distinguished properties of the solar system is the (past) presence of the short-lived radionuclide ^{26}Al (τ = 1 Myr) in its earliest formed solids (Davis et al. 2014). Magnesium-26 anomalies attributed to the decay of ^{26}Al were first identified in the calcium-, aluminium-rich inclusions (CAIs) from the primitive meteorite Allende in 1976 (Lee et al. 1976). Since then, many measurements have been done, and the initial concentration of ^{26}Al in CAIs – assimilated to that of the whole solar protoplanetary disk (SPD) – is relatively well established. Since CAIs are the first meteoritic solids to have formed in the SPD, ^{26}Al injection occurred very early, possibly during the first 10^5 yr of the SPD evolution (Connelly et al. 2012). Though the solar system was endowed with a wide diversity of short-lived radionuclides in term of half lives and chemical properties (Dauphas & Chaussidon 2011), aluminium-26 is especially important because it helps build a detailed chronology of physical processes in the SPD (Davis et al. 2014). In addition, it was the main heat source of the planetesimals and embryos from which terrestrial planets formed (Johansen et al. 2015) and, as such, has shaped their chemical and mineralogical evolution.

Since its discovery, the origin of ^{26}Al has remained elusive. Unlike longer-lived radionuclides, its concentration in the nascent solar system is far too elevated to be accounted for by steady-state Galactic nucleosynthesis (Meyer & Clayton 2000). In addition, its short half life compared to typical evolutionary timescales of star-forming regions (Montmerle et al. 2006) imposes a last-minute origin, either internal or external. Because it is unlikely ^{26}Al was synthesized in situ via irradiation of the SPD gas or solids by protosolar cosmic rays (Gounelle et al. 2013; Fitoussi et al. 2008), it almost certainly had a stellar origin. Though asymptotic giant branch (AGB) stars produce large quantities of ^{26}Al during cool bottom processing (Wasserburg et al. 2006; Lugaro et al. 2012), which can be released in the interstellar medium (ISM), the probability of associating an AGB star with a star-forming region is virtually nought (Kastner & Myers 1994). A massive star (i.e. more massive than 8 $M_{\odot}$) is therefore the most likely source of ^{26}Al in the early solar system (Davis et al. 2014).

The goal of the present paper is to calculate the probability of forming planetary systems having an ^{26}Al enrichment similar to that of our solar system. In Sect. 2, we critically examine experimental data concerning short-lived radionuclides and previous models that attempted to account for the presence of ^{26}Al in in the solar system. In Sect. 3 we calculate the fraction of ^{26}Al-rich planetary systems in the Galaxy using the model proposed by Gounelle & Meynet (2012), and in Sect. 4, we discuss the commonness of our solar system, as well as the implications of our findings for the evolution of planetary systems in general.

2. Experimental data and interpretative models

2.1. Experimental data

As mentioned in the Introduction, almost 40 years of measurements have led to a relatively good understanding of ^{26}Al concentration in the SPD. The abundance of ^{26}Al in CAIs, given by the ratio $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0 \approx 5.2 \times 10^{-5}$, is considered to be the average initial value of the SPD (Davis et al. 2014). Lower ratios observed in chondrules (millimetre-sized quenched silicate droplets ubiquitous in chondrites; Krot et al. 2009) are usually attributed to their later formation relative to CAIs (e.g. Luu et al. 2015). This difference can also be due to a heterogeneous distribution of ^{26}Al in the SPD (Gounelle & Russell 2005; Connelly et al. 2012). The existence of numerous ^{26}Al-free CAIs (Krot et al. 2012) and of ubiquitous Mg isotopic anomalies in bulk meteorites (Larsen et al. 2011) are strong arguments in favour of some heterogeneity of the ^{26}Al distribution in the SPD. Though the exact level of heterogeneity is unknown, it is unlikely that the initial $(^{26}Al/^{27}Al)_0$ ratio in the bulk protoplanetary disk has differed from that of CAIs by a factor larger than 3 (Schiller et al. 2015). Using the initial $(^{26}Al/^{27}Al)_0$ ratio mentioned above, one can calculate the initial solar system concentration of $C_{\odot}[^{26}Al] = (^{26}Al/^{27}Al)_0 \times (^{27}Al/^{1}H) \times Z_{\odot} \times M_{26}/M_1 = 3.3 \times 10^{-9}\ M_{\odot}/M_{\odot}$ = 3.3 ppb (parts per billion) where M_{26} and M_1 are the molar masses of ^{26}Al, $Z_{\odot}$ = 0.71 is the (proto)solar metallicity, and $^{27}Al/^{1}H = 3.5 \times 10^{-6}$ (Lodders 2003).

Iron-60 (τ = 3.7 Myr), which decays onto ^{60}Ni, is another key short-lived radionuclide whose origin is often discussed in conjunction with that of ^{26}Al (see below). Because mass-independent nickel isotopic anomalies are ubiquitous in CAIs (Birck & Lugmair 1988), the search for the earlier presence of ^{60}Fe had to be performed in other primitive samples such as chondrules. From chondrule in situ measurements, the inferred initial ^{60}Fe abundance in the early solar system was considered to be high ($(^{60}Fe/^{56}Fe)_0$ up to $\sim 10^{-6}$) until recently (e.g. Mostefaoui et al. 2005; Tachibana et al. 2006). Telus et al. (2012) and Ogliore et al. (2011), however, demonstrated that these high ratios were due to improper data reduction. Using another instrumental approach based on the analysis of bulk chondrites and differentiated meteorites, a diversity of groups have suggested that the initial solar system $^{60}Fe/^{56}Fe$ ratio was two orders of magnitude lower than previously thought, with an upper limit of 1×10^{-8} (Tang & Dauphas 2012; Moynier et al. 2011; Quitté et al. 2011). Very few chondrules still show higher initial ratios (Mishra & Chaussidon 2014), possibly because of nickel redistribution on the mineral scale (Chaussidon & Barrat 2009) due to fluid-assisted thermal metamorphism. When adopting $(^{60}Fe/^{56}Fe)_0 = 1 \times 10^{-8}$ (Moynier et al. 2011; Tang & Dauphas 2012; Davis et al. 2014) and using $^{56}Fe/^{1}H = 3.2 \times 10^{-5}$ (Lodders 2003), the solar system's initial concentration was $C_{\odot}[^{60}Fe] = 1.3 \times 10^{-11}\ M_{\odot}/M_{\odot}$ = 0.013 ppb. Though data are limited, given that ^{60}Fe has been positively detected in very few objects, if any, this short-lived radionuclide seems to have been homogeneously distributed in the SPD (Tang & Dauphas 2012). With these abundances in hand, we can calculate an important property of the nascent solar system, namely its initial $(^{60}Fe/^{26}Al)_0$ mass ratio, which we find equal to 3.9×10^{-3}. It is difficult to give an error estimate on that number given the difficulties attached to determining the ^{60}Fe initial abundance. Given that we have adopted a high value for the initial $(^{60}Fe/^{56}Fe)_0$ ratio, the number we give for the solar system's initial $(^{60}Fe/^{26}Al)_0$ mass ratio is an upper limit.

2.2. Previous models

Stars form in clusters from the dense phase of molecular clouds (Montmerle et al. 2006). The larger a cluster, the higher the probability it contains a massive star (only ~0.3% of the total number of stars in a given cluster is more massive than 8 $M_{\odot}$). Once formed, massive stars strongly influence their environment (Boneberg et al. 2015). They photo-dissociate the surrounding gas, creating a zone of hot and diffuse gas (HII region) where star formation is inhibited, and emit powerful winds. They end their lives in very energetic supernova (SN) explosions. Because of their short lifetimes (4 Myr for a 40 $M_{\odot}$ star and 9 Myr for a 20 $M_{\odot}$ star; Schaller et al. 1992), the most massive stars reach their final states of evolution in the very area were they where born (Williams 2010). They therefore have the possibility to inject fresh nucleosynthetic products into their nascent molecular cloud. Because during their lifetime (~10 Myr, see Hennebelle & Falgarone 2012), giant molecular clouds (GMCs) experience

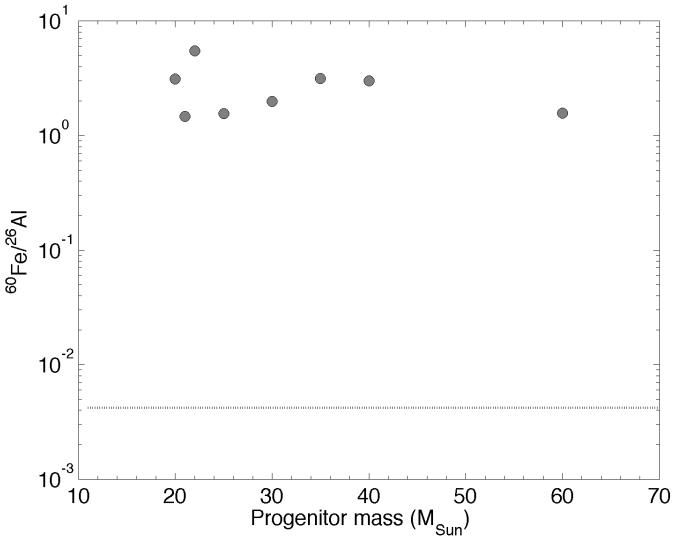

Fig. 1. Initial $^{60}Fe/^{26}Al$ mass ratio of supernovae for progenitor masses varying from 20 to 60 $M_{\odot}$ (Woosley & Heger 2007) and corresponding to the range of stellar masses that have been considered by modelers (see text). The solar system initial mass ratio $(^{60}Fe/^{26}Al)_0 = 3.9 \times 10^{-3}$ is shown for comparison.

different episodes of star formation, second generations of stars can form with newly synthesized nucleosynthetic products, provided these have efficiently mixed with the dense, star-forming, phase. Iron-60 has probably followed that route into the nascent solar system. It has been inherited from supernovae whose progenitors belonged to a previous star generation of the same GMC (Gounelle et al. 2009).

Until now, the dominant model accounting for the presence of ^{26}Al in the nascent solar system has been that of the nearby supernova (Cameron & Truran 1977). This model stipulates that having reached the end of its evolution and exploding as a supernova, a massive star delivered ^{26}Al directly into the SPD (Ouellette et al. 2010) or alternatively into the presolar dense core (Boss & Keiser 2010). All SN models consider that supernova progenitors had masses varying between 20 and 60 $M_{\odot}$ (Boss & Keiser 2010; Ouellette et al. 2010). The rationale for excluding low-mass supernovae is that stars with masses lower than 20 $M_{\odot}$ have lifetimes that are longer than (or comparable to) those of molecular clouds, so they explode when the star-forming region where they were born has disappeared. Very massive supernovae are very rare and extremely disruptive for their environments (Chevalier 2000).

Though possible, this model encounters a number of difficulties. First, supernovae produce copious amounts of other short-lived radionuclides along with ^{26}Al. This is especially the case for ^{60}Fe, which is synthesized during the hydrostatic and explosive phases of stellar evolution (Woosley & Heger 2007). The most up-to-date nucleosynthetic models (Woosley & Heger 2007) calculate that the $^{60}Fe/^{26}Al$ mass ratio in he bulk supernova ejecta (i.e. taking all nucleosynthetic products into account above the mass cut that is constrained by observed neutron star masses) varies between 1.5 and 5.5 for the considered mass range (Fig. 1). This is far in excess of the $(^{60}Fe/^{26}Al)_0$ ratio of the nascent solar system, which was below 3.9×10^{-3} (see Sect. 1). The variability in the composition of SN ejecta, which are spatially structured into clumps, has been invoked as a possible solution out of that caveat (Pan et al. 2012). Though the condensation temperature of iron is slightly lower than that of aluminium

(Lodders 2003), both elements are refractory (see e.g. Fig. 1b of Yin 2005) and are expected to fully condense in supernovae ejecta, as confirmed by the recent observations of the Supernova 1987A (Matsuura et al. 2011). It is therefore very unlikely that putative ^{26}Al enrichments relative to ^{60}Fe in SN clumps reach the factor of ∼1000 needed to fill the gap between the observed and the calculated values (Fig. 1).

Finally, these models lack observational support. To deliver ^{26}Al at the solar abundance, the invoked SN needs to be at a small (<2 pc), fine-tuned, distance from the nascent solar system whose exact value depends on the SN mass (Looney et al. 2006). The Orion Nebula has often been presented as the paradigm of such a situation (Hester et al. 2004). However, the disks that are observed now around the ≈1 Myr central star (θ^1 Ori C) will be gone when that star explodes as a supernova, either because they will have been photo-evaporated (Bally et al. 1998) or because they will have formed planets (Williams 2010). Even if these disks survive in the harsh environment created by the massive star, putative ^{26}Al injection will occur when the disk is at least a few Myr old, which does not correspond to the solar system's situation. In fact, because ^{26}Al-rich CAIs have the oldest absolute Pb-Pb ages (Connelly et al. 2012), it implies ^{26}Al was present in the solar system during the earliest phases of the disk.

More generally, supernova remnants (SNR) adjacent to star-forming regions happen to be rare. While hundreds of galactic SNRs are known (Green 2009), there are only a handful of them associated with molecular dense phases which are in any case too far away to receive any significant amount of ^{26}Al (Sashida et al. 2013). For example, the distance between the Trifid star-forming region and the SNR W28 is d = 15 pc (adopting an Earth distance of 2 kpc, Vaupré et al. 2014). At such a distance, a protoplanetary disk of size r = 100 AU would receive a mass of ^{26}Al, $M_{26} = \frac{1}{4}(r/d)^2\ Y_{26}$ (Gounelle & Meibom 2008) assuming perfect mixing and instantaneous injection (i.e. neglecting ^{26}Al decay). With a SN yield of $Y_{26} = 1.3 \times 10^{-4}\ M_\odot$ (for a progenitor mass of 40 $M_\odot$, Woosley & Heger 2007), M_{26} equals $3.4 \times 10^{-14}\ M_\odot$. Adopting a disk mass of 0.01 $M_\odot$, it corresponds to a concentration of $3.4 \times 10^{-12}\ M_\odot/M_\odot$, three orders of magnitude lower than the solar system value. Because the mixing efficiency is by definition lower than 1 (and possibly as low as a few %, Boss & Keiser 2010), and because ^{26}Al decays relatively fast (compared to evolutionary timescales of star formation), the discrepancy between the SN-injected ^{26}Al concentration in a nearby disk with the solar system initial abundance is even larger.

Massive star winds, which are rich in ^{26}Al and contain no ^{60}Fe, represent a promising alternative to SNe as the ^{26}Al delivery agent (Arnould et al. 2006, 1997; Gaidos et al. 2009; Tatischeff et al. 2010). Recently, Gounelle & Meynet (2012) have proposed a model in which ^{26}Al is injected by a massive star wind into a collected dense shell of mass ∼1000 $M_\odot$ surrounding an HII region centred on the massive star. Detailed calculations, based on the most up-to-date wind modelling, have shown that as long as the massive star, baptized *Coatlicue* (Gounelle 2013), is more massive than 32 $M_\odot$, the abundance of ^{26}Al in the shell is equal to or larger than that of the solar system. When the collected shell has become dense enough and gravitationally unstable, it collapses and a second generation of ^{26}Al-rich stars forms. The Sun would have been one of these second-generation stars. Because it belongs to a previous star generation and having provided ^{26}Al, *Coatlicue* can be considered as the Sun's parent star. In that model, the newly formed protostar-disk system is too far away (5–10 pc) from the massive star to be contaminated by the ^{60}Fe released by the

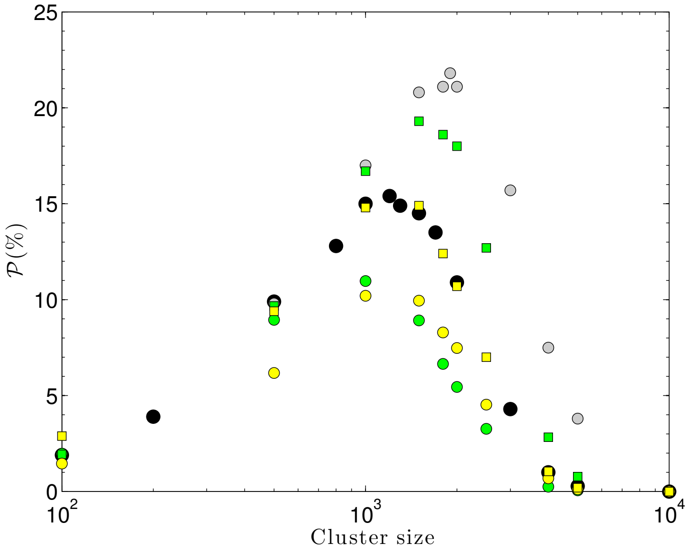

Fig. 2. Probability $\mathcal{P}$ (in %), as a function of the cluster size N, to realize the double condition: 1) the number of stars with mass higher than $M_{\rm SN}$ is less than $n_{\rm SB}$; and 2) one star at least has a mass greater than $M_{\rm min}$, where the values $n_{\rm SB}$, $M_{\rm min}$, and $M_{\rm SN}$ are set to vary. For each point, the IMF (see text) was simulated 10 000 times. Filled circles: $n_{\rm SB}$ = 5, $M_{\rm min}$ = 32 $M_\odot$, and $M_{\rm SN}$ = 8 $M_\odot$. Grey circles: all are the same, but $M_{\rm SN}$ = 10 $M_\odot$. Green circles: all the same, but $n_{\rm SB}$ = 4. Green squares: all the same, but $n_{\rm SB}$ = 6. Yellow circles: all the same, but $M_{\rm min}$ = 40 $M_\odot$. Yellow squares: all the same, but $M_{\rm min}$ = 25 $M_\odot$. This figure, essentially identical to Fig. 8 of Gounelle & Meynet (2012), is shown for clarity.

subsequent SN explosion. This mechanism therefore does not suffer from the difficulty encountered by the nearby SN model, namely an overproduction of ^{60}Fe relative to ^{26}Al and the solar value. Because ^{26}Al injection occurs over a 4π solid angle, the need to be at a fined-tuned, unrealistically short (see above) distance from the massive star is relaxed. Finally, this model corresponds to the commonly observed astrophysical setting of induced star formation within dense shells (Deharveng et al. 2010) and to the long known paradigm of the collect-and-collapse star formation mechanism (Elmegreen & Lada 1977).

3. The fraction of ^{26}Al-rich planetary systems

Gounelle & Meynet (2012) identified the most likely parent cluster size by imposing two constraints discussed below: (i) the cluster contained at least one star more massive than $M_{\rm min}$; and (ii) it contained fewer than $n_{\rm SN}$ stars more massive than $M_{\rm SN}$ = 8 $M_\odot$. Simulating the stellar initial mass function (IMF) in a Monte-Carlo fashion[1], they calculated the probability distribution $\mathcal{P}(N)$ to realize that double condition as a function of the parent cluster size N (Fig. 2). For fiducial parameters, $M_{\rm min}$ = 32 $M_\odot$ and $n_{\rm SN}$ = 5, $\mathcal{P}(N)$ has a distinct peak for $N \approx 1200$. If calculation parameters (such as $M_{\rm min}$, $n_{\rm SN}$) are set to vary, the value of the peak does not change much and remains within the range of 1000–2000 stars (Fig. 2).

The fraction of clusters that realize that double condition reads $\mathcal{F} = \int \mathcal{P}(N) P_{\rm cl}(N) {\rm d}N / \int P_{\rm cl}(N) {\rm d}N$, where $P_{\rm cl}(N) = {\rm d}N_{\rm cl}/{\rm d}N$ is the number distribution of stellar clusters. The distribution ${\rm d}N_{\rm cl}/{\rm d}N$ has been determined both within the Galaxy

[1] The stellar initial mass function (IMF) has been mimicked using the generating function described in Kroupa et al. (1993). The fraction $f_{\rm SN}$ of stars more massive than 8 $M_\odot$ (i.e. which will go SN) is 2.4×10^{-3}, and the average stellar mass is 0.5 $M_\odot$.

Table 1. Fraction $\mathcal{F}$ of clusters (in %) that do realize the dual condition: (i) having at least one star more massive than $M_{\rm min}$; and (ii) containing less than $n_{\rm SN}$ stars more massive than 8 $M_\odot$.

	$n_{\rm SN}$ = 5 $M_{\rm min}$ = 32 $M_\odot$	$n_{\rm SN}$ = 4 $M_{\rm min}$ = 32 $M_\odot$	$n_{\rm SN}$ = 7 $M_{\rm min}$ = 32 $M_\odot$	$n_{\rm SN}$ = 5 $M_{\rm min}$ = 25 $M_\odot$	$n_{\rm SN}$ = 5 $M_{\rm min}$ = 40 $M_\odot$
α = 1.8	5.6	4.7	6.5	8.2	3.8
α = 2	**5.2**	4.5	5.9	7.7	3.6
α = 2.2	4.8	4.2	5.2	7.1	3.3

Notes. These numbers are the integration of the probability distributions shown in Fig. 2 over the cluster size distribution $P_{\rm cl}(N) = {\rm d}N_{\rm cl}/{\rm d}N \approx N^{-\alpha}$. The fiducial condition, given by $M_{\rm min}$ = 32 $M_\odot$, $n_{\rm SN}$ = 5, and α = 2 (see text) is outlined in bold font. Errors on the calculated probability due to the finite number of IMF realizations (10 000) are below 5% relative.

and outside and found to vary as $N^{-\alpha}$ with $\alpha \approx 2$ for clusters' sizes ranging from $N_{\rm min} = 10^2$ to $N_{\rm max} = 5 \times 10^5$ (Lada & Lada 2003; Adams et al. 2006; Williams & Gaidos 2007). Using the fiducial probability distribution depicted in Fig. 2 and the N^{-2} cluster size distribution, a cluster fraction of 5.2% is calculated (Table 1). Exploring the whole range of model parameters (i.e. $n_{\rm SN}$, $M_{\rm min}$), and varying α between 1.8 and 2.2, the cluster fraction lies between 3.3 and 8.2% (Table 1).

This is not in a strict sense the probability of forming a star containing ^{26}Al at the solar value, since the ^{26}Al-rich stars belong to the second generation of stars of the cluster. To calculate that probability, one needs to estimate the ratio of secondary stars produced in the shell to the number of primary stars. Adopting a mean star formation efficiency of 16% (Kainulainen et al. 2014) and a mean stellar mass of 0.5 $M_\odot$ (see footnote #1), one finds that the Sun formed together with 320 stars in the 1000 $M_\odot$ shell. Therefore, the ratio of the secondary to primary stars amounts to 320/1200 = 0.27. Multiplying $\mathcal{F}$ by this ratio yields a total probability that varies from 0.9 to 2.2% with a preferred value of 1.4% (corresponding to our fiducial case, $n_{\rm SB}$ = 5, $M_{\rm min}$ = 32 $M_\odot$ and $M_{\rm SN}$ = 8 $M_\odot$). Taking observed variations of a factor 2 of the star formation efficiency into account (Kainulainen et al. 2014; Lada & Lada 2003) would change the total probability by a factor of 2. This is insignificant considering our approach that aims at identifying a model outline consistent with star formation observations and at giving orders-of-magnitude numbers. Though details of the model could and should be investigated, the order of magnitude of the probability is very robust because the curves depicted in Fig. 2 encompass all possibilities for producing solar-like ^{26}Al concentrations. It has been obtained by requiring two simple, though key properties of the parent stellar cluster.

The first requirement comes from the necessity to have enough ^{26}Al present in the massive star wind. Gounelle & Meynet (2012) showed that it happens for stars more massive than 32 $M_\odot$, possibly 25 $M_\odot$, if one considers uncertainties in ^{26}Al nucleosynthetic yields. It is, however, safe to exclude stars with masses lower than 20 $M_\odot$ because they underproduce ^{26}Al by orders of magnitude compared to what is required (Gounelle & Meynet 2012). This would remain true even if the ^{26}Al abundance in the SPD was a factor 3 lower than what was adopted (Schiller et al. 2015). The second requirement is also stringent. If the number of massive stars in the parent cluster is too large ($n > n_{\rm SN}$), the HII region becomes a superbubble and opens in the ISM. Because pressure in the superbubble region is far lower than pressure in the dense region, wind-produced elements tend to mix with the superbubble hot gas rather than with the cold dense gas. It corresponds to the Orion situation where hot gas flows out the Eridani superbubble generated by several massive stars (Güdel et al. 2008). In such a situation, ^{26}Al emitted by the wind follows that escape route instead of being incorporated into the shell. Relaxing the adopted constraint and imposing $n_{\rm SN}$ = 7 would develop the right tail of the bell-shape curve shown in Fig. 2 and increase the probability (Table 1).

The robustness of our calculation to changes in the whole set of parameters indicates that the presence of ^{26}Al in the dense shell does not depend on the model's details once the basic requirements stated above are satisfied. This is somehow satisfying because it would be pretentious to claim that the exact setting of the Sun formation has been identified. Contrasting with the necessity to have a nearby SN sitting at a fine-tuned, unrealistically short distance from the nascent solar system, the present model offers a range of solutions that are all taken into account in the probability calculation presented above. What will vary is the actual content of ^{26}Al in the shell, which might depend on the precise mass of *Coatlicue*, that of the collected shell and the mixing efficiency of the wind material with the shell. This last parameter encompasses the model microphysics, such as the wind interaction with the HII region and with the shell, and depends on the photoionization rate and the density of the surrounding gas (Dale et al. 2014). Determining that parameter value using numerical simulations is desirable to better constrain our model and to improve, on a general basis, our knowledge of the mixing between the hot and the cold phases of the ISM. The mixing efficiency is expected to depend on the spatial scale of mixing. We note that our model can accommodate mixing efficiencies as low as a few percentage points (Gounelle & Meynet 2012). A distribution of ^{26}Al abundance is therefore expected in other solar systems. Calculating that precise distribution is the scope of another work.

4. Discussion

4.1. Global vs. local origin

Our mechanism, which relies on the wind of a single massive star, operates on a local scale. In such a model, only a fraction (a few %) of planetary systems formed in a given molecular cloud contain a significant abundance of ^{26}Al. It does contrast with models, considering that ^{26}Al is delivered on the scale of an entire (giant) molecular cloud (Gaidos et al. 2009; Young 2014). In these models, ^{26}Al produced both by massive stars winds and supernovae explosions is injected within a given (giant) molecular cloud by tens of stars. According to these authors, all planetary systems formed in such a context began with the same ^{26}Al concentration, which is the average ^{26}Al abundance of the GMC under consideration.

There is indeed no doubt that ^{26}Al is present at significant levels in molecular clouds. It has actually been detected via γ-ray astronomy in several star-forming regions (Diehl et al. 2006). Because the average ^{26}Al concentration of Orion and other star-forming regions is similar to that of the nascent solar system, Young (2014) and Jura et al. (2013) argue that the (high) solar concentration of ^{26}Al is a common feature of all star-forming regions. This argument relies on the assumption that ^{26}Al released by supernovae and massive star winds is homogeneously distributed in the considered molecular clouds, implicitly assuming that ^{26}Al mixes instantaneously and perfectly with the star-forming, dense phase of the molecular clouds. This double assumption is likely to be incorrect, as was discussed above (Sect. 3). The hot, ^{26}Al-rich, gas will have the tendency to preferably mix with the low density phases of the ISM, unless it is trapped, as in the closed shell model. In other words, the abundance of ^{26}Al measured by γ-ray astronomers in star-forming regions, though representative of the bulk molecular cloud abundance, might be significantly higher than that of the dense phase of the same molecular cloud and therefore than that of planetary systems formed in the same star-forming regions.

In addition, if ^{26}Al in the solar system was inherited from a molecular cloud, one would expect the solar system to have a $(^{60}\text{Fe}/^{26}\text{Al})_0$ ratio identical to that of the ISM. If the collapse timescales – depending on the amount of turbulence, the intensity of magnetic fields, and other complex parameters (McKee & Ostriker 2007) – exceed a few ^{26}Al half lives, the solar system's initial $(^{60}\text{Fe}/^{26}\text{Al})_0$ ratio is even expected to be higher than that of ISM because ^{26}Al decays much faster than ^{60}Fe. Both radionuclides have now been identified in the ISM via γ-ray astronomy (Diehl 2014). The measured ISM flux ratio $^{60}\text{Fe}/^{26}\text{Al}$ ratio is 0.15 (Wang et al. 2007), which translates into a mass ratio of 0.35. The ISM $^{60}\text{Fe}/^{26}\text{Al}$ mass ratio is therefore two orders of magnitude higher than the solar value of 3.9×10^{-3} (see Sect. 1), ruling out that both radionuclides were inherited from the ISM. Despite the observational evidence, and to keep alive the inherited model, Young (2014) proposed to decrease the theoretical ^{60}Fe abundance in molecular clouds by assuming that stars more massive than 30 $M_\odot$ do not explode as SNe. These stars would not contribute to the ^{60}Fe inventory, bringing the theoretical ISM $^{60}\text{Fe}/^{26}\text{Al}$ ratio closer to that of the solar system. Because stars more massive than 30 $M_\odot$ contribute to less than 50% of the ^{60}Fe production[2], this proposition cannot resolve the two orders of magnitude discrepancy between the model and observations. Furthermore, the recent discovery of a supernova whose progenitor mass was far above the threshold of 30 $M_\odot$ is at odds with that solution (Gal-Yam et al. 2014). Finally, if ^{26}Al was inherited from the natal molecular cloud, it would be homogeneously distributed in the SPD, which is contrary to observations (Krot et al. 2012). As discussed by Gounelle & Meynet (2012), some heterogeneity in the ^{26}Al distribution is expected in the dense shell model because the shell collapse timescale (a few 10^5 yr) is comparable to the ^{26}Al half life.

4.2. A common solar system

One percent or so is a relatively high number. It means that, though not the rule, the presence of ^{26}Al in planetary systems is not at all an exception. It implies that billions of low-mass stars and planetary systems in the Galaxy were born with significant amounts of ^{26}Al. Our probability estimate is comparable to the probability estimate calculated by Williams & Gaidos (2007) and Gounelle & Meibom (2008) for injection by a single SN. These works, however, have vastly overestimated the fraction of disks (or cores) present within a few pc of a SN and therefore the probability of ^{26}Al injection by a SN. In fact, when massive stars are ready to explode as SNe, they are surrounded by HII regions of radius >5–10 pc where star formation does not occur (Hennebelle et al. 2009). It implies that the fraction of disks present within a few pc of a SN is closer to zero than to 30% as was assumed by e.g. Gounelle & Meibom (2008) who based their estimate on the observations of disks surrounding a young star (far from the relevant supernova stage). If that constraint had been taken into account by Williams & Gaidos (2007) and Gounelle & Meibom (2008), the probability estimate for a single SN would have been virtually nought, in agreement with observations (see above Sect. 1).

More importantly, our model corresponds to the observation that triggered star formation is a generic mode of star formation (Hennebelle et al. 2009). Though not all stars form that way, a significant fraction of them do. The commonness of the solar system agrees with the observation that our Sun does not seem to have many other special properties. Although it has long been claimed that it had C and O elemental abundances that are distinct from the local ISM (Meyer 1989), this view has been abandoned (Turck-Chièze et al. 2004), especially now that the abundance of the light elements in the Sun has been revised downwards (Asplund et al. 2009). The higher solar system $^{18}\text{O}/^{17}\text{O}$ ratio compared to that of the local ISM (Young et al. 2011) is interpreted as either a normal outcome of Galactic chemical evolution (Nittler & Gaidos 2012) or as an outprint of the supernovae that delivered ^{60}Fe in the solar molecular cloud (Young et al. 2011). In many respects, our Sun is therefore a banal star, which should not require a special origin such as one imposed by the presence of a supernova having a well-defined mass and sitting at a finely tuned distance from the nascent solar system.

As the fraction of massive stars relative to the total number of stars is 2.4×10^{-3} (see footnote #1), one massive star was possibly born with the Sun in the dense shell, together with a few hundred stars (see above). The dynamical and electromagnetic influence of that massive star onto the newly formed disk of gas and planetesimals could have been the trigger for highly eccentric Kuiper belt objects or the early SPD truncation (Adams 2010), though other causes have been proposed (Dukes & Krumholz 2012).

4.3. Implications for the early evolution of planetary systems

The question of the origin of ^{26}Al and its probability of being realized are far from academic questions, since its presence or absence has the virtue of influencing the subsequent evolution of planetary systems. Given its elevated initial abundance, ^{26}Al has been the main heating source of 10–1000 km chondritic planetesimals and planetary embryos from which solar system planets formed (Grimm & McSween 1993). Its main effect has been to promote differentiation of the largest objects and fluid circulation in the ice-rich planetesimals, leading to drastic changes in the mineralogy, petrography, and structure of the building blocks of planets. In ^{26}Al-rich planetary systems, planetary embryos acquire a differentiated structure very quickly. Dating of iron meteorites that come from embryos' cores indicates that this process occurred within 1 Myr of the solar system's formation (Kruijer et al. 2012).

The high collision rates in the early solar system imply that these differentiated embryos probably lost their crust and possibly their mantles very early and therefore that the Earth and other terrestrial planets were built from collisionally evolved

[2] According to the IMF, stars more massive than 30 $M_\odot$ represent fewer than half of the total number of stars more massive than 20 $M_\odot$, i.e. those stars contributing to the ^{60}Fe (and ^{26}Al) inventory in a given molecular cloud.

bodies (i.e. having lost a fraction – or all – of their silicate part) rather than from chondritic, undifferentiated, bodies (O'Neill & Palme 2008). Therefore, the inventory of volatiles, as well as the redox state of terrestrial planets in an ^{26}Al-free planetary system, would probably have been different from what they are in our terrestrial planets, everything else being the same. More importantly, ^{26}Al-heating of ice-rich planetesimals lead to the loss of water vapour in space (Young et al. 1999), drastically changing the bulk water/rock ratio of the planetesimal. Had ^{26}Al not been present, ice-rich planetesimals would not have endured any geological evolution and kept their initial water ice content. Their accretion onto Earth and other planets would have lead to an excess of water compared to the present inventory, which might have covered the entire planet, modified the key silicate/carbonate cycle (Treguer & De La Rocha 2013), and possibly prevented the development of continental life.

Finally, the circulation of water due to ^{26}Al decay heating has led to the modification of the inventory of planetesimals organics inherited from the ISM. The CI1 chondrites have endured far more hydrothermal processing than any other meteorites (Zolensky & McSween 1988). The nature and concentration of the amino acids they contain is different than those found in CM2 chondrites, which have been altered to a lesser degree (Ehrenfreund et al. 2001). Amino acids are also less abundant in CI1 chondrites compared to CM2 chondrites (Glavin et al. 2010). Had hydrothermal alteration been pervasive and all CM2 chondrites turned into CI1 chondrites, the possible inventory of amino acids and other organic molecules delivered to Earth by chondrites and available for life development might have been drastically different, and life itself could have followed a different evolutionary path.

5. Conclusions

Though favoured until recently, the SN nearby model is unlikely to account for the past presence of ^{26}Al in the nascent solar system, since it does not satisfy either astronomical or cosmochemical constraints. The model that is most respectful of star-forming regions' observations is the injection of ^{26}Al in a dense shell collected by the wind of a massive star, followed by the shell gravitational collapse and the formation of a few hundred ^{26}Al-rich stars. The model outline is quite robust to parameter change and allows for a wide range of possible solutions. It is an important first step in the understanding of the astrophysical context of the Sun's formation, though many details concerning the microphysics of wind interaction with the surrounding gas remain to be explored.

The number of stars in the Galaxy that satisfy the identified setting is around one percent (with a factor of a few uncertainty), in agreement with astronomical observations of star-forming regions that have shown that the proposed setting is a generic, though not universal, mode of star formation. It implies that billions of stars in the Galaxy, hence planetary systems, were born with a significant amount of ^{26}Al. As for the solar system, the presence of ^{26}Al might have strongly influenced exoplanetary evolution in other planetary systems by limiting the amount of water present at the planets' surface and in enabling a wide range of interstellar amino acids to be incorporated in primitive exo-Earths.

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