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Number of stars in the Sun's birth cluster revisited

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ABSTRACT

The Sun is thought to have been formed within a star cluster. The coexistence of ^{26}Al-rich and ^{26}Al-poor calcium–aluminum-rich inclusions indicates that a direct injection of ^{26}Al-rich materials from a nearby core-collapse supernova would be expected to occur in the first 10^5 years of the existence of the Solar System. Therefore, at least one core-collapse supernova ought to occur within the duration of star formation in the Sun's birth cluster. Here, we revisit the number of stars in the Sun's birth cluster from the point of view of the probability of experiencing at least one core-collapse supernova within the finite duration of star formation within the birth cluster. We find that the number of stars in the birth cluster may be significantly greater than that previously considered, depending on the duration of star formation.

Key words. meteorites, meteors, meteoroids – supernovae: general – stars: Wolf-Rayet – open clusters and associations: general

1. Introduction

The majority of stars form within star clusters (e.g., Lada & Lada 2003) and our Solar System is also thought to have been formed within a cluster, based on a number of indications (e.g., Adams 2010). For example, some of trans-Neptunian objects, including (90 377) Sedna, exhibit a substantial heliocentric eccentricity and perihelion distance (e.g., Brown et al. 2004) and the most plausible scenario for their formation is a close encounter with a passing star in the Sun's birth cluster (e.g., Morbidelli & Levison 2004; Brasser et al. 2006). Parts of presolar grains, whose isotopic compositions are significantly anomalous by comparison with the average solar composition, originate from core-collapse supernovae (CCSNe; e.g., Nittler & Ciesla 2016), and the chromium isotopic heterogeneity found in various chondritic meteorites might be evidence of the injection of dust grains from a CCSN (e.g., Sugiura & Fujiya 2014; Fukai & Arakawa 2021).

An injection of dust grains into the Solar System from a nearby CCSN is also a classical scenario for the origin of short-lived radionuclides (SLRs) found in meteorites (e.g., Takigawa et al. 2008; Ouellette et al. 2010). Such SLRs are radioactive nuclides that were present in the early Solar System but have since been extinguished, and their existence in the early Solar System is recorded in the structure of meteorites as excesses of the daughter isotopes. Huss et al. (2009) reviewed the stellar nucleosynthetic processes in the context of stellar evolution and concluded that massive stars in the range of 20–60 $M_{\odot}$ ($M_{\odot}$ is the solar mass) would be plausible sources of SLRs when we assume a direct injection from CCSNe. The range of the progenitor mass was discussed based on the amount of production for several SLRs, including ^{26}Al and ^{60}Fe.

The oldest dust particles condensed in the Solar System are calcium-and-aluminum-rich inclusions (CAIs) that are 4.567 billion years old, based on their lead isotopic ages (e.g., Amelin et al. 2002). Although the majority of primitive (i.e., unmelted) CAIs are uniformly enriched in ^{26}Al (e.g., MacPherson et al. 2012), some unusual CAIs show the order-of-magnitude lower initial abundance of ^{26}Al. Platy hibonite crystals (PLACs) are classified into those unusual CAIs and they are regarded as the oldest CAIs based on their high condensation temperature and large nucleosynthetic anomalies (e.g., Sahijpal & Goswami 1998; Kööp et al. 2016), although their origins are still under debate (e.g., Larsen et al. 2020; Desch et al. 2022). In addition, CAIs with fractionation and unidentified nuclear effects (FUN CAIs) also have low and varied initial abundances of ^{26}Al, and they are thought to have been formed prior to normal CAIs (e.g., Park et al. 2017). The coexistence of ^{26}Al-rich and ^{26}Al-poor CAIs would serve as evidence of a direct injection of ^{26}Al-enriched dust grains into the solar nebula (or the solar molecular cloud core) in the epoch of CAI formation (e.g., Sahijpal & Goswami 1998; Holst et al. 2013). As the duration of CAI formation (i.e., the formation age spread of CAIs) is a few 10^5 years or less (e.g., Thrane et al. 2006; Connelly et al. 2012; Kawasaki et al. 2020), the direct injection event would have occurred in the first 10^5 years of Solar System formation. We note that the initial abundance of ^{26}Al recorded in CAIs would not be altered even if additional injection of ^{26}Al-enriched materials into the solar nebula occurred after the condensation of CAIs. This timescale is one order of magnitude shorter than the duration of star formation in star clusters (e.g., Kruijssen et al. 2019; Fujii et al. 2021) and we can expect that at least one CCSN would occur in the Sun's birth cluster during its star formation period.

The condition for acquiring at least one CCSN in the birth cluster has been covered in previous studies (e.g., Adams 2010; Portegies Zwart 2019). These works have evaluated the minimum number of stars in the birth cluster based on the probability for existing at least one massive star whose mass is large enough to trigger a CCSN with ejection of SLR-rich dust grains. For example, Adams (2010) demonstrated that the probability

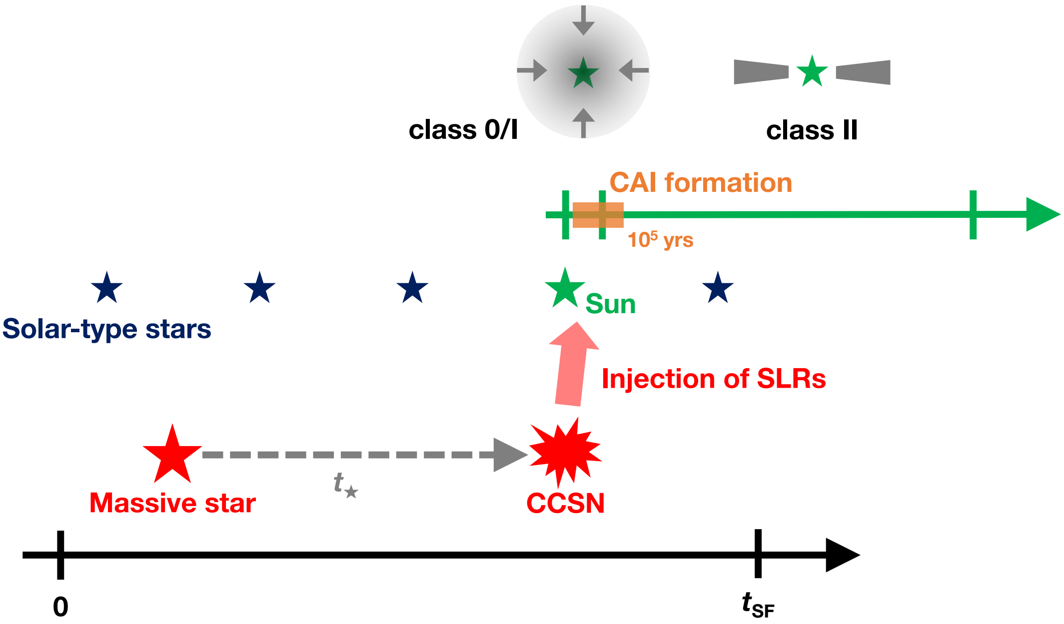

Fig. 1. Schematic of the direct injection of SLRs into the early Solar System within the birth cluster. Massive stars those were born in the cluster would trigger CCSNe when they finished their lifetime, $t_\star$. To explain the coexistence of ^{26}Al-rich and ^{26}Al-poor CAIs in the early Solar System, a direct injection of SLR-rich dust grains from a CCSN should occur during CAI formation in the Solar System. A necessary condition for Solar System formation is that at least one CCSN occurs in the birth cluster within the duration of star formation, t_{SF}.

for hosting at least one massive star whose mass is higher than 25 $M_\odot$ reaches 50% when the number of stars in the cluster is approximately 800. We note, however, that these estimates did not consider the timing of CCSNe in the cluster, and the existence of massive stars in the cluster does not support the occurrence of CCSN events during its star formation period. This is because there is a finite time lag for the birth of a massive star and its explosion. As both the time lag (i.e., the lifetime of a massive star) and the duration of star formation in a cluster are several to tens of million years (e.g., Schaller et al. 1992), the lifetime of a massive star could have a large impact on the evaluation of the number of stars in the birth cluster.

Figure 1 shows the schematic of the direct injection of SLRs into the early Solar System within the birth cluster. Stars continuously formed within the birth cluster and the duration of star formation, t_{SF}, would last for several million years. Massive stars those were born in the cluster would trigger CCSNe when they finished their lifetime, $t_\star$. A large number of solar-type stars also formed in the cluster. To explain the coexistence of ^{26}Al-rich and ^{26}Al-poor CAIs in the early Solar System, a direct injection of SLR-rich dust grains from a CCSN would be expected to occur during CAI formation in the Solar System. As the duration of CAI formation is a 10^5 years and negligibly shorter than t_{SF}, a necessary condition for Solar System formation is for at least one CCSN to occur in the birth cluster within t_{SF}.

In this paper, we revisit the number of stars in the Sun's birth cluster from the point of view of a direct injection of SLRs from a CCSN into the early Solar System. We calculate the probability for acquiring at least one CCSN within the finite duration of star formation in the birth cluster. We find that the estimated number of stars in the birth cluster is significantly larger than that previously considered, especially for cases where the duration of star formation is far lower than 10 million years; for instance, for $t_{SF} = 5$ Myr, the probability is 50% when the number of stars in the cluster is approximately 2×10^4, which is 25 times larger than the estimation calculated by Adams (2010).

2. Model

In this section, we briefly describe basic equations used in this study. We calculate the expected number of CCSN events during the star formation period of the birth cluster using probabilistic approach. Our model is similar to that considered in Adams (2010). The novel point of this study is that we consider the impacts of finite duration of star formation and the lifetimes of massive stars on the expected number of CCSN events.

2.1. Initial mass function

It is known that the maximum stellar mass in the birth cluster, m_{max}, depends on the total cluster mass, M_{cl} (e.g., Weidner & Kroupa 2006). Portegies Zwart (2019) provides an approximated relation between m_{max} and M_{cl} as follows:

$$\log_{10} \frac{m_{max}}{M_\odot} = -0.76 + 1.06 \log_{10} \frac{M_{cl}}{M_\odot} - 0.09 \left(\log_{10} \frac{M_{cl}}{M_\odot} \right)^2, \quad (1)$$

where $M_\odot$ is the solar mass. The minimum stellar mass, m_{min}, is set to be $m_{min} = 0.07\, M_\odot$.

The initial mass function of stars in the birth cluster, $\xi(m_\star)$, is given by a broken power-law mass function (e.g., Kroupa 2002; Kroupa & Jerabkova 2021), where $m_\star$ is the stellar mass. For low-mass stars of $m_{min} < m_\star < m_{tra}$, the initial mass function is given by:

$$\xi(m_\star) = k \left(\frac{m_\star}{m_{min}} \right)^{-1.3}, \quad (2)$$

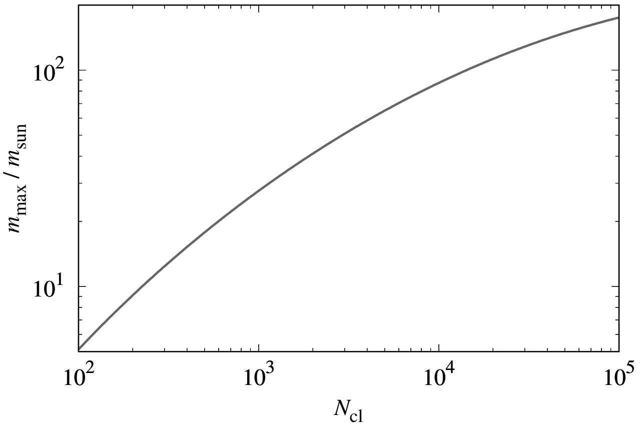

Fig. 2. Relation between the maximum stellar mass in the birth cluster, m_{max}, and the total number of stars, N_{cl}.

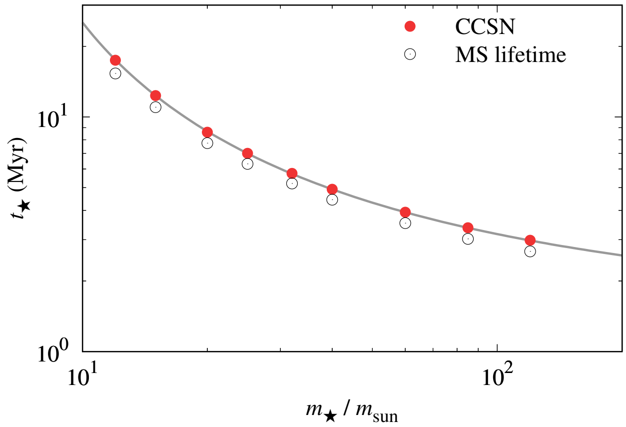

Fig. 3. Relation between the lifetime of stars (i.e., the time lag from the birth of a star to trigger CCSN), $t_\star$, and the stellar mass, $m_\star$. We also show the main-sequence lifetime (i.e., the duration of H-burning) as reference. Circle plots are data taken from Ekström et al. (2012) and the solid curve is the empirical fitting.

where $m_{tra} = 0.5\,M_\odot$ is the transition mass for the broken power-law and k is the constant. For high-mass stars of $m_{tra} \le m_\star < m_{max}$, the initial mass function is given by

$$\xi(m_\star) = k\left(\frac{m_{tra}}{m_{min}}\right)^{-1.3}\left(\frac{m_\star}{m_{tra}}\right)^{-2.3}. \quad (3)$$

The initial mass function satisfies the following equation:

$$\int_{m_{min}}^{m_{max}} dm_\star\, m_\star \xi(m_\star) = M_{cl}. \quad (4)$$

The expected total number of stars in the birth cluster, N_{cl}, is

$$\int_{m_{min}}^{m_{max}} dm_\star\, \xi(m_\star) = N_{cl}. \quad (5)$$

Figure 2 shows the relation between m_{max} and N_{cl}. As massive stars of $20\,M_\odot < m_\star < 60\,M_\odot$ can trigger CCSNe that might provide SLRs to the early Solar System, the N_{cl} value for a cluster that hosts a progenitor of a plausible CCSN is $N_{cl} \gtrsim 600$.

2.2. Time distribution of star formation

Each star in the birth cluster forms at different time within the finite duration. The formation rate of stars whose mass is $m_\star$ and the birth time is t, $n_{SF}(m_\star, t)$, is given by:

$$n_{SF}(m_\star, t) = \xi(m_\star) f(m_\star, t), \quad (6)$$

where $f(m_\star, t)$ is the normalized time distribution of star formation, which is defined as:

$$\int_0^{t_{SF}} dt\, f(m_\star, t) = 1, \quad (7)$$

and t_{SF} is the duration of star formation in the birth cluster. In this study, we assume that $f(m_\star, t)$ is given as the following mass- and time-independent equation for simplicity:

$$f(m_\star, t) = \frac{1}{t_{SF}}. \quad (8)$$

We note that $f(m_\star, t)$ must depend on both $m_\star$ and t in reality. Direct numerical simulations of the star cluster formation in giant molecular clouds (e.g., Fukushima et al. 2020; Fukushima & Yajima 2021) are necessary for discussng the details of $f(m_\star, t)$. Fukushima & Yajima (2021) calculated the temporal evolution of the total stellar mass in their numerical simulations of star cluster formation. The total stellar mass increased with time and saturated at several times of free-fall timescale of star-forming molecular clouds. From their Fig. 7, $f(m_\star, t)$ takes the maximum at around the free-fall timescale, although the timing must depend on the physicochemical properties of star-forming molecular clouds including the initial density profile and the metallicity in reality (see Sect. 4.1).

2.3. Lifetime of stars

The lifetime of stars depends on the stellar mass (e.g., Schaller et al. 1992). Assuming that the lifetime of the star, $t_\star$, is given by the sum of durations of H-burning and He-burning, we obtained an empirical relation between $t_\star$ and $m_\star$ for non-rotating massive stars by using the numerical results shown in Ekström et al. (2012):

$$\frac{t_\star}{1\,\mathrm{Myr}} = 3.25\left(\log_{10}\frac{m_\star}{4.69\,M_\odot}\right)^{-1.80} + 1.22. \quad (9)$$

Figure 3 shows $t_\star$ as a function of $m_\star$, and we found that $t_\star > 4$ Myr for massive stars of $20\,M_\odot < m_\star < 60\,M_\odot$, namely, the progenitors of plausible CCSNe (e.g., Huss et al. 2009). It is important to note that no CCSNe that provide SLRs to the early Solar System would be triggered within t_{SF} if the lifetime of the most massive star in the cluster, $t_{\star,max}$, is longer than t_{SF}.

3. Results

When we assume that the situation that a CCSN occurred at the timing of the birth of the Solar System, we need (at least) one CCSN event within the duration of star formation in the birth cluster. In this section, we discuss the probability for acquiring at least one CCSN within the duration of star formation.

3.1. Probability for acquiring at least one CCSN within the duration of star formation

The event rate of an CCSN whose progenitor mass is $m_\star$ and the explosion time is t, $n_{SN}(m_\star, t)$ is given by:

$$n_{SN}(m_\star, t) = n_{SF}(m_\star, t - t_\star). \quad (10)$$

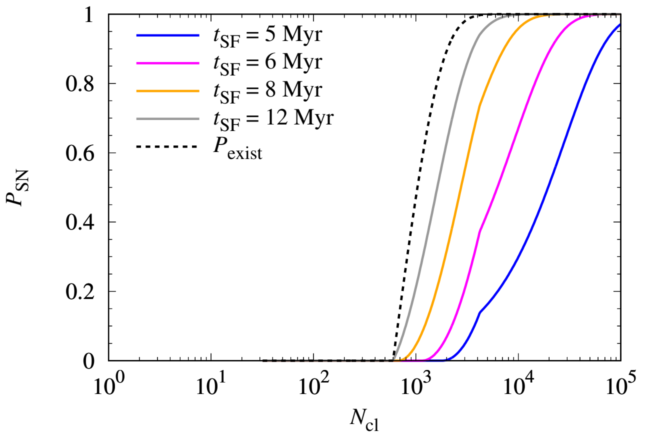

Fig. 4. Probability of acquiring at least one core-collapse supernova with mass in the range of 20–60 $M_\odot$ within the duration of star formation, P_{SN}. Here, we assume that m_{max} depends on N_{cl} and it is given by Eq. (1).

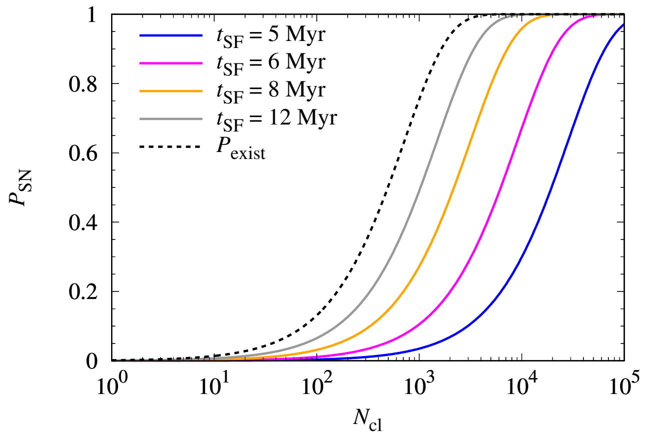

Fig. 5. Probability for acquiring at least one core-collapse supernova with mass in the range of 20–60 $M_\odot$ within the duration of star formation, P_{SN}. Here, we assume that m_{max} = 100 $M_\odot$ and does not depend on N_{cl}.

Then the total event rate of CCSNe at t, $p_{SN}(t)$, is

$$p_{SN}(t) = \int_{20\,M_\odot}^{60\,M_\odot} dm_\star\, n_{SN}(m_\star, t). \tag{11}$$

The cumulative number of CCSNe within the duration of star formation in the birth cluster, Z_{SN}, is given as follows:

$$Z_{SN} = \int_0^{t_{SF}} dt\, p_{SN}(t). \tag{12}$$

Then the probability for acquiring at least one CCSN, P_{SN}, would be given by (see Appendix A):

$$P_{SN} = 1 - \exp(-Z_{SN}). \tag{13}$$

Figure 4 shows P_{SN} and its dependence on N_{cl} and t_{SF}. The minimum number of N_{cl} for $P_{SN} > 0$ depends on t_{SF}; this is because $t_{\star,max}$ depends on N_{cl}, and $P_{SN} = 0$ when $t_{SF} \leq t_{\star,max}$.

The birth cluster of the Sun needs to satisfy the condition of $P_{SN} > 0$ and probably meets the condition $P_{SN} \gtrsim 0.5$ (e.g., Adams 2010). We note that the threshold value of $P_{SN} = 0.5$ was arbitrarily chosen in Adams (2010), although 50% would be a fair threshold from the perspective of whether at least one CCSN event is likely to occur within t_{SF} in a star cluster (or not). If $P_{SN} \ll 1$ for a star cluster, no solar-type stars would have experienced a direct injection of SLR-rich materials in the star cluster. We acknowledge, however, that a solar-type stars could have experienced a direct injection even if the P_{SN} for each star cluster is $P_{SN} \ll 1$ when we consider dozens of star clusters.

Our results indicate that the total number of stars in the birth cluster would be $N_{cl} \gtrsim 2 \times 10^4$ if t_{SF} = 5 Myr, although the final tally depends on the shape of $f(m_\star, t)$. When the duration of star formation is t_{SF} = 12 Myr, the required condition for N_{cl} is mitigated as: $N_{cl} \gtrsim 2 \times 10^3$.

Considering the relation between timings of star formation and explosion (see Eq. (10)), P_{SN} depends on the shape of $f(m_\star, t)$. If $f(m_\star, t)$ is low at $t \sim 0$ and increases with time for massive stars of 20–60 $M_\odot$, P_{SN} is lower than that for time-independent $f(m_\star, t)$. Recent astronomical observations of nearby star-forming regions (e.g., Kumar et al. 2020, 2022) have revealed that low-mass stars are born in filamentary structures, while massive stars are born in hubs formed via mergings of multiple filaments. We speculate that $f(m_\star, t)$ is low at $t \sim 0$ for massive stars if star clusters formed from hub-filament systems, although it should be tested in future numerical simulations and astronomical observations.

3.2. Impacts of the initial mass function on P_{SN}

In the previous section, we consider the dependency of m_{max} on N_{cl}, as shown in Fig. 2. However, some previous studies did not consider this dependence, however, they did assume m_{max} as a constant. For instance, in Adams (2010), m_{max} is set to 100 $M_\odot$. Here, we show how the assumption of m_{max} affects the probability for acquiring at least one CCSN within the duration of star formation.

Figure 5 shows P_{SN} and its dependence on N_{cl} and t_{SF}. In contrast to Figure 4, P_{SN} is nonzero for any N_{cl} when t_{SF} is longer than the lifetime of stars whose mass is 60 $M_\odot$($\simeq$4 Myr). We found that P_{SN} barely changes with the assumption of m_{max} for the cases of $N_{cl} \gtrsim 4 \times 10^3$. This N_{cl} corresponds to the condition for m_{max} = 60 $M_\odot$. As both mass and number of stars in the cluster is dominated by smaller stars, the number of massive stars with mass in the range of 20–60 $M_\odot$ scarcely depends on the assumption of m_{max} when $m_{max} > 60\,M_\odot$.

We also calculate the probability for existing at least one massive star whose mass is large enough to trigger a plausible CCSN. The expected number of progenitors formed in the birth cluster, Z_{exist}, is given by:

$$Z_{exist} = \int_{20\,M_\odot}^{60\,M_\odot} dm_\star\, \xi(m_\star). \tag{14}$$

Then the probability for existing at least one progenitor, P_{exist}, would be given by

$$P_{exist} = 1 - \exp(-Z_{exist}). \tag{15}$$

We note that $P_{SN} \to P_{exist}$ for $t_{SF} \to \infty$ by definition.

The classical estimation by Adams (2010) corresponds to the dashed line of Fig. 5, whereas our results those take into consideration the finite duration of star formation are the solid lines in Fig. 4. We found that $P_{exist} > 0.5$ is achieved when $N_{cl} > 500$ and m_{max} is independent of N_{cl}. In contrast, when we consider both finite t_{SF} and variable m_{max}, $P_{SN} > 0.5$ is achieved only when $N_{cl} \gg 1000$. For example, $N_{cl} \gtrsim 2 \times 10^4$ if t_{SF} = 5 Myr

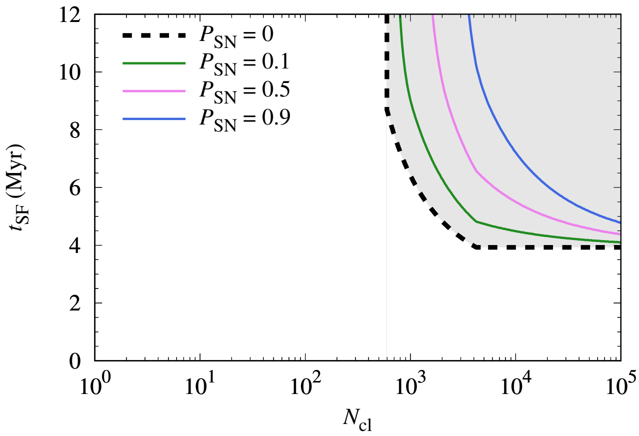

Fig. 6. Contour chart of P_{SN} in N_{cl}–t_{SF} plane. We note that $P_{SN} = 0$ outside the shaded area.

and this is 40 times larger than the value obtained from a classical way. In particular, the impact of finite t_{SF} on the estimate of N_{cl} is significant, as shown in Figs. 4 and 5.

3.3. Plausible parameters of the Sun's birth cluster in N_{cl}–t_{SF} plane

Figure 6 is the contour chart of P_{SN} in N_{cl}–t_{SF} plane. We found that $P_{SN} = 0$ outside the shaded area of Fig. 6. The boundary (dashed line) consists of three regions: (1) $N_{cl} = N_{cl}|_{m_{max}=20\,M_\odot} =$ const. and $N_{cl}|_{m_{max}=20\,M_\odot}$ is the number of stars in the cluster for $m_{max} = 20\,M_\odot$; (2) $t_{SF} = t_{\star,max}$ and $t_{\star,max}$ is the lifetime of the most massive star in the cluster; and (3) $t_{SF} = t_\star|_{m_\star=60\,M_\odot} =$ const. and $t_\star|_{m_\star=60\,M_\odot}$ is the lifetime of stars whose mass is $60\,M_\odot$.

As $t_\star|_{m_\star=60\,M_\odot} \simeq 4$ Myr (see Fig. 3), P_{SN} sharply decreases when $t_{SF} \to 4$ Myr. For example, if we set $N_{cl} = 10^4$, we obtain: $P_{SN} = 2 \times 10^{-3}$ for $t_{SF} = 4$ Myr, $P_{SN} = 0.3$ for $t_{SF} = 5$ Myr, and $P_{SN} = 0.7$ for $t_{SF} = 6$ Myr.

The condition for $P_{SN} = 0.1$ is not significantly different from the condition for $P_{SN} = 0$ in the N_{cl}–t_{SF} plane. This corresponds to the sharp increase of P_{SN} around $P_{SN} = 0$ (as shown in Fig. 4) and this is the feature for the model with variable m_{max}. We therefore regard the shaded region as the possible parameters of the Sun's birth cluster.

When we focus on the condition for $P_{SN} > 0.5$ (magenta solid line), the plausible number of stars in the Sun's birth cluster would be larger than 2×10^3 when $t_{SF} < 10$ Myr. Moreover, the plausible number would be $N_{cl} > 2 \times 10^4$ when a much shorter timescale of $t_{SF} < 5$ Myr is assumed.

4. Discussion

4.1. Considering the duration of star formation in the birth cluster

Understanding the duration of star formation in the birth cluster is crucial for determining the plausible N_{cl}. Fujii et al. (2021) studied the formation of massive star cluster that satisfies $N_{cl} > 10^4$, and they found that the duration of star formation in star clusters has a significant variation. For a large cluster formed in a numerical simulation of Fujii et al. (2021), the duration of star formation is $t_{SF} > 5$ Myr, while another small cluster showed a very short duration of approximately 1 million years (see their Figure 25).

The maximum value of t_{SF} would be evaluated from the sum of free-fall timescale and disruption timescale of star-forming giant molecular clouds due to expansion of H II bubbles (e.g., Fukushima et al. 2020). As the efficiency of photoionization feedback strongly depends on the initial surface density of star-forming giant molecular clouds (e.g., Fukushima & Yajima 2021), t_{SF} may also depend on the initial surface density and thus it should depend on the cluster radius. Future studies on this point is needed to evaluate the physical parameters of the Sun's birth cluster.

4.2. Dynamical constraints on the birth cluster

It is not only the existence of SLRs, but also the dynamical properties of Solar System bodies that set crucial constraints on N_{cl}. Portegies Zwart (2009) and Adams (2010) reviewed the constraints on the number of stars (N_{cl}) and radius (R_{cl}) of the Sun's birth cluster. Close encounters of stars within a distance of 100 au can easily destroy the planetary system and the sharp truncation of the Kuiper belt at approximately 50 au could be reproduced when the distance of the closest encounter, b, is in the range of 150–200 au (e.g., Kobayashi & Ida 2001). Considering the dynamical evaporation of the star cluster, Kobayashi & Ida (2001) estimated the relation among b, N_{cl} and R_{cl} as follows (see also Adams & Laughlin 2001):

$$b \sim 200\left(\frac{N_{cl}}{2 \times 10^3}\right)\left(\frac{R_{cl}}{2\,\mathrm{pc}}\right)^{-1}\,\mathrm{au}. \tag{16}$$

Concha-Ramírez et al. (2019) listed N_{cl} and R_{cl} for various star clusters and star-forming regions that host class II young stellar objects. These authors reported that $N_{cl} \simeq 2000$ and $R_{cl} \simeq 1$ pc for the Orion Trapezium cluster and $N_{cl} \simeq 12\,700$ and $R_{cl} \simeq 52$ pc for the Lupus cloud star-forming region. Using these values, we obtained b for these two regions: $b \sim 100$ au for the Orion Trapezium cluster and $b \sim 800$ au for the Lupus cloud star-forming region. A large cluster with $N_{cl} \sim 10^4$ and $R_{cl} \simeq 10$ pc might be plausible from the points of view of dynamical and cosmochemical constraints.

We note that the estimation above is based on the assumption that stars are distributed homogeneously within a cluster. However, in reality, stars in clusters would be initially distributed in a fractal (e.g., Goodwin & Whitworth 2004). Portegies Zwart (2019) argued that b tends to be small when a cluster with an initial fractal distribution is considered.

4.3. Considering the timing of injection event

There are two major scenarios devised to explain the direct injection of SLRs from a nearby CCSN: either an injection to the molecular cloud core (e.g., Cameron & Truran 1977; Vanhala & Boss 2002; Boss et al. 2008; Gritschneder et al. 2012) or an injection to the circumstellar disk (e.g., Clayton 1977; Chevalier 2000; Ouellette et al. 2007, 2010). In the following, we briefly review these scenarios.

Molecular cloud cores are the progenitors of protostars and the gravitational collapse of molecular cloud cores forms stars and their circumstellar disks. The duration of this stage is typically several 10^5 years and it corresponds to the class 0/I young stellar objects (e.g., Dauphas & Chaussidon 2011). The injection to the molecular cloud core is regarded not only as the event for SLR enrichment but also as the trigger for the collapse of the protosolar molecular cloud core (e.g., Li et al. 2014; Kinoshita et al. 2021).

Another scenario is the direct injection of dust particles to the earliest phase of the circumstellar disk around the young Sun corresponding to class II young stellar objects. Ouellette et al. (2010) found that the injection efficiency depends on the size of dust particles and 0.1–1 micron-sized dust particles could be implanted to the circumstellar disk. Nearby CCSNe would have a significant impact not only on the abundance of SLRs, but also on the structural evolution of the circumstellar disk. Portegies Zwart et al. (2018) numerically investigated interactions between a supernova (both irradiation and blast wave) and the Solar circumstellar disk. They concluded that the observed misalignment between the Sun's equator and the ecliptic plan (e.g., Beck & Giles 2005) and the sharp truncation of the Kuiper belt (e.g., Allen et al. 2001) could be explained by a nearby CCSN event.

We note that the timing of injection event could also affect the isotopic heterogeneity found in various stable isotopes. Fukai & Arakawa (2021) mentioned that injection of clumpy supernova ejecta into the circumstellar disk around the young Sun could be reasonable from the point of view of the nucleosynthetic chromium isotopic variation recorded in carbonaceous chondrites, although we cannot rule out the possibility that the injection event has occurred in the molecular cloud core stage.

4.4. Injection of SLRs from Wolf-Rayet winds

Wolf-Rayet (WR) stars are massive evolved stars whose surface composition has been altered by mass loss and internal mixing. The minimum initial mass for a star to become a WR star is approximately 25 $M_\odot$ at the solar metallicity, although the threshold mass depends on its rotation (e.g., Georgy et al. 2012; Smith 2014). For non-rotating WR stars, the mass loss due to WR winds starts after their main-sequence and the lifetime in the WR phase is less than 0.5 million years (e.g., Meynet & Maeder 2003; Georgy et al. 2012).

Also, WR winds might play an important role as injectors of SLRs (e.g., Arnould et al. 1997, 2006; Gounelle & Meynet 2012). As WR winds are enriched in ^{26}Al but depleted in ^{60}Fe, several studies (e.g., Tang & Dauphas 2015) have regarded WR stars as one of the most plausible sources for the origin of SLRs in the early Solar System (see Appendix B).

There are two types of scenarios for introducing SLRs from WR stars: a direct injection to the solar nebula by WR winds (e.g., Portegies Zwart 2019) and the enrichment of SLRs before the formation of the parental molecular cloud core (e.g., Gounelle & Meynet 2012; Dwarkadas et al. 2017). In the latter scenario, the Sun would be born in the dense shell around a WR star together with a huge numbers of solar siblings.

We note that the time interval of the start of the WR phase and the following CCSN explosion would be approximately 0.5 million years or less. This timescale is comparable to the timescale for collapse of the molecular cloud core. Therefore, we can imagine that both WR wind and CCSN could contribute to the enrichment of SLRs in the early Solar System. In future studies, we would aim to investigate what would be happen if both WR wind and CCSN occurred within the Sun's birth cluster.

4.5. Alternative scenarios without direct injection events

In this study, we focus on the case of SLRs in the early Solar System being directly injected from nearby sources. We note, however, that several studies have proposed that sequential star formation events and/or self-enrichment in parental molecular clouds as a possible explanation of the abundance of SLRs in the early Solar System (e.g., Gounelle & Meynet 2012; Gounelle 2015; Fujimoto et al. 2018; Forbes et al. 2021; Desch et al. 2022).

Although these scenarios have the capacity to naturally explain the abundance of SLRs recorded in normal CAIs, we point out that these scenarios would have difficulty in reproducing the coexistence of ^{26}Al-poor unusual CAIs and ^{26}Al-rich normal CAIs. Kuffmeier et al. (2016) performed numerical simulations on the giant molecular cloud scale that can trace the star formation history and abundance of ^{26}Al in star-forming gas. They reported that ^{26}Al/^{27}Al ratio of accreting gas onto a newborn star is spatially and temporally homogeneous during its class 0/I phase. This might indicate that all CAIs have same initial value of ^{26}Al/^{27}Al in the framework of these scenarios – which appears inconsistent with meteoritical evidence.

Kuffmeier et al. (2016) and Larsen et al. (2020) speculated that FUN CAIs and PLACs might be formed via the selective thermal processing of presolar dust grains. Their scenario requires that CAIs formed via partial evaporation and recondensation with spatial partitioning; however, whether the CAI formation region satisfies these requirements or not is unclear. Future studies on the particle dynamics in the innermost region of the solar nebula would be needed.

5. Summary

There are several pieces of evidence available to indicate that our Solar System was formed within a star cluster. Injection of SLR-rich dust grains into the Solar System from a nearby CCSN is a classical scenario for the origin of SLRs found in meteorites, including ^{26}Al and ^{60}Fe. Although the majority of primitive CAIs are uniformly enriched in ^{26}Al, some unusual CAIs (i.e., FUN CAIs and PLACs) show a lower initial abundance of ^{26}Al by one order-of-magnitude. The coexistence of ^{26}Al-rich and ^{26}Al-poor CAIs is usually interpreted as the evidence of the direct injection of ^{26}Al-enriched dust grains into the Solar System in the epoch of CAI formation. As the duration of CAI formation is approximately 10^5 years, the direct injection event would have occurred in the first 10^5 years of the Solar System formation. Therefore, at least one CCSN would occur in the Sun's birth cluster during its star formation period that would be typically several million years (Fig. 1).

The condition for acquiring at least one CCSN in the birth cluster has been investigated in previous studies (e.g., Adams 2010). These works have evaluated the minimum number of stars in the birth cluster based on the probability for existing at least one massive star whose mass is large enough to trigger a CCSN, with an ejection of SLR-rich dust grains. However, those studies did not consider the timing of CCSNe in the cluster and the existence of massive stars in the cluster does not support the occurrence of CCSN events during its star formation period.

In this paper, we revisited the number of stars in the Sun's birth cluster from the point of view of direct injection of SLRs from a CCSN to the early Solar System. We calculated the probability for acquiring at least one CCSN within the finite duration of star formation in the birth cluster (Fig. 4). We found that the estimated number of stars in the birth cluster, $N_{\rm cl}$, is significantly larger than that previously considered, especially for cases where the duration of star formation, $t_{\rm SF}$, is far less than 10 million years.

The plausible number of stars in the Sun's birth cluster would be $N_{\rm cl} > 2 \times 10^3$ when $t_{\rm SF} < 12$ Myr (Fig. 6), although the actual calculation depends on a number of assumptions. Moreover, the plausible number would be $N_{\rm cl} > 2 \times 10^4$ when much shorter timescale of $t_{\rm SF} < 5$ Myr is assumed. In contrast, the minimum number of stars without consideration of the timing of explosion, namely, the lower limit of $N_{\rm cl}$ obtained in a classical way, is approximately 500 (Fig. 5). In other words, our novel constraint is an order of magnitude higher than previous estimates.

Understanding the evolution of the solar nebula in the birth cluster is essential to unveiling how the Earth formed. The effects of nearby massive stars on disk evolution (e.g., external photoevaporation and stellar feedback from winds and supernovae; Concha-Ramírez et al. 2019) should depend on $N_{\rm cl}$, $t_{\rm SF}$, and the geometry of the cluster. Future studies on the disk evolution around solar-type stars in a large star cluster taking the impact of finite $t_{\rm SF}$ into account would be crucial.

We acknowledge that the issue of whether the source of SLRs is a CCSN or a WR star is still under debate. Moreover, whether a direct injection event contributes to the SLR enrichment of the Solar System or not is also controversial. We discussed these topics in Sect. 4. These uncertainties on the origin of SLRs must have a great impact on the evaluation of $N_{\rm cl}$ and $t_{\rm SF}$ for the Sun's birth cluster. This point ought to be the subject of in-depth studies in the future.

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Appendix A: Derivation of the relation between $Z_{\rm SN}$ and $P_{\rm SN}$

Here, we briefly derive the relation between $Z_{\rm SN}$ and $P_{\rm SN}$. We set the time interval Δt as $\Delta t = t_{\rm SF}/N$, where N is a large integer. When Δt is sufficiently small, the probability that no CCSN occur between the time t and $t + \Delta t$ is equal to $1 - p_{\rm SN}(t)\Delta t$. Then, the probability for acquiring no CCSN within $t_{\rm SF}$, $1 - P_{\rm SN}$, is given by the following equation:

$$1 - P_{\rm SN} = \lim_{\Delta t \to 0} \prod_{n=0}^{N-1} [1 - p_{\rm SN}(n\Delta t)\Delta t]. \tag{A.1}$$

By taking the logarithm of both sides, the equation above is converted as follows:

$$\begin{aligned} \log(1 - P_{\rm SN}) &= \lim_{\Delta t \to 0} \sum_{n=0}^{N-1} \log[1 - p_{\rm SN}(n\Delta t)\Delta t] \\ &= -\lim_{\Delta t \to 0} \sum_{n=0}^{N-1} p_{\rm SN}(n\Delta t)\Delta t \\ &= -Z_{\rm SN}. \end{aligned} \tag{A.2}$$

Therefore, we obtained the relation between $Z_{\rm SN}$ and $P_{\rm SN}$:

$$P_{\rm SN} = 1 - \exp(-Z_{\rm SN}). \tag{A.3}$$

Appendix B: Abundance of ^{60}Fe in the early Solar System

The initial abundance of ^{60}Fe is key to unveiling the source of SLRs in the early Solar System. It is known that ^{60}Fe is scarcely produced by energetic-particle irradiation around the young Sun (e.g., Lee et al. 1998) and that its presence requires an extrasolar contribution from massive stars.

The initial ratio of ^{60}Fe/^{56}Fe has been investigate in a large number of studies (e.g., Tachibana & Huss 2003; Tang & Dauphas 2012, 2015; Telus et al. 2018; Trappitsch et al. 2018). Tachibana & Huss (2003) measured troilite grains in least metamorphosed ordinary chondrites and reported that the initial ratio of ^{60}Fe/^{56}Fe for the Solar System would be in the range between 2.8×10^{-7} and 4×10^{-7}. As the steady-state ratio for the interstellar medium is 2.6×10^{-8} (Wasserburg et al. 1996), these authors claimed that enrichment of ^{60}Fe-rich materials is required shortly before or during Solar System formation. Takigawa et al. (2008) found that the abundance ratio of ^{60}Fe and ^{26}Al would be consistent with a injection of ejecta from a CCSN with mixing and fallback (e.g., Nomoto et al. 2006). The range of the initial mass of the progenitor would be 20–40$m_\odot$, based on the original analysis of Takigawa et al. (2008) and the finding from Huss et al. (2009) that the mixing-fallback process could potentially explain the abundance ratio of SLRs for stars up to 60$m_\odot$.

The initial value of ^{60}Fe/^{56}Fe is still under debate, however, Tang & Dauphas (2015) measured chondrules in the least metamorphosed ordinary chondrite (Semarkona) and they reported a much lower level of ^{60}Fe/^{56}Fe (see also Kodolányi et al. 2022a,b). The initial abundance obtained from their measurements corresponds to ^{60}Fe/^{56}Fe ratio of $(1.01 \pm 0.27) \times 10^{-8}$ and no injection event is needed to explain this low abundance of ^{60}Fe. Telus et al. (2018) also measured chondrules in least metamorphosed ordinary chondrites, concluding that the initial ^{60}Fe/^{56}Fe ratio would be 8.5×10^{-8} to 5.1×10^{-7}, namely, higher than the interstellar medium background. This is consistent with a scenario positing that the early Solar System was enriched in materials from CCSN ejecta.