TRACKING THE DISTRIBUTION OF $^{26}$Al AND $^{60}$Fe DURING THE EARLY PHASES OF STAR AND DISK EVOLUTION

Michael Kuffmeier$^1$, Troels Frostholt Mogensen$^1$, Troels Haugbølle$^1$, Martin Bizzarro$^2$, and Ake Nordlund$^1$

$^1$Centre for Star and Planet Formation, Niels Bohr Institute and Natural History Museum of Denmark, University of Copenhagen, Øster Voldgade 5-7, DK-1350 Copenhagen K, Denmark; kueffmeier@nbi.ku.dk
$^2$Centre for Star and Planet Formation and Natural History Museum of Denmark, University of Copenhagen, Øster Voldgade 5-7, DK-1350 Copenhagen, Denmark

Received 2016 January 28; revised 2016 May 2; accepted 2016 May 16; published 2016 July 18

ABSTRACT

The short-lived $^{26}$Al and $^{60}$Fe radionuclides are synthesized and expelled into the interstellar medium by core-collapse supernova events. The solar system’s first solids, calcium–aluminum refractory inclusions (CAIs), contain evidence for the former presence of the $^{26}$Al nuclide defining the canonical $^{26}$Al/$^{27}$Al ratio of $\sim 5 \times 10^{-5}$. A different class of objects temporally related to canonical CAIs are CAIs with fractionation and unidentified nuclear effects (FUN CAIs), which record a low initial $^{26}$Al/$^{27}$Al of $10^{-6}$. The contrasting level of $^{26}$Al between these objects is often interpreted as reflecting the admixing of the $^{26}$Al nuclides during the early formative phase of the Sun. We use giant molecular cloud scale adaptive mesh-refinement numerical simulations to trace the abundance of $^{26}$Al and $^{60}$Fe in star-forming gas during the early stages of accretion of individual low-mass protostars. We find that the $^{26}$Al/$^{27}$Al and $^{60}$Fe/$^{56}$Fe ratios of accreting gas within a vicinity of 1000 au of the stars follow the predicted decay curves of the initial abundances at the time of star formation without evidence of spatial or temporal heterogeneities for the first 100 kyr of star formation. Therefore, the observed differences in $^{26}$Al/$^{27}$Al ratios between FUN and canonical CAIs are likely not caused by admixing of supernova material during the early evolution of the proto-Sun. Selective thermal processing of dust grains is a more viable scenario to account for the heterogeneity in $^{26}$Al/$^{27}$Al ratios at the time of solar system formation.

Key words: ISM: abundances – magnetohydrodynamics (MHD) – methods: numerical – protoplanetary disks – stars: abundances – stars: formation

1. INTRODUCTION

Giant molecular clouds (GMCs) are the primary reservoirs of cold, star-forming gas in the Galaxy. Astronomical observations and numerical simulations of star-forming regions suggest that GMCs have typical lifetimes of a few tens of Myr (Bash et al. 1977; Blitz & Shu 1980; Fukui et al. 1999; Kawamura et al. 2009; Dobbs et al. 2014, p. 3; Padoan et al. 2015), during which multiple episodes of star formation may take place. Stars more massive than eight solar masses eventually end their lives in type II supernova explosions and, during these events, pollute their environments with nucleosynthetic products. As such, the nucleosynthetic make-up of a protostellar core in a GMC is expected to reflect a mixture of an old galactically inherited component with younger supernova-derived material, including freshly synthesized radioactive $^{26}$Al and $^{60}$Fe, produced during the lifetime of the GMC. The $\gamma$-ray emission from radioactive $^{26}$Al and $^{60}$Fe nuclei, observable throughout the Milky Way due to the low opacity of $\gamma$-rays, have been used to determine the current average ISM abundance of $^{26}$Al and $^{60}$Fe and, hence, an estimate of the galactic $^{60}$Fe/$^{26}$Al ratio (Diehl et al. 2006; Wang et al. 2007).

Meteorites and their components provide insights into the formation history of the earliest solar system, including the birthplace of the Sun. The most primitive meteorites, chondrites, contain calcium–aluminum-rich inclusions (CAIs) representing the oldest dated solar system solids, formed 4567.30 ± 0.16 Myr ago (Connelly et al. 2012). These sub-millimeter-to-centimeter objects are thought to have formed as fine-grained condensates from a gas of approximately solar composition, in a region with high ambient temperature ($>1300$ K) and low total pressures ($10^{-4}$ bar) (Tielens & Allamandola 1987; Ebel & Grossman 2000), possibly during a brief (<10,000 years) (Larsen et al. 2011) heating event temporally associated with the very earliest phase of the proto-Sun (Krot et al. 2009). The presence in CAIs of the decay products of the short-lived radioisotope $^{10}$Be, formed by solar energetic particle irradiation (McKeegan et al. 2000), is further evidence that they formed in the vicinity of the proto-Sun. Importantly, CAIs typically contain evidence for an early presence of $^{26}$Al, defining a canonical initial $^{26}$Al/$^{27}$Al ratio of $\sim 5 \times 10^{-5}$ (MacPherson et al. 1995; Jacobsen et al. 2008; Larsen et al. 2011). This initial abundance is approximately 10 times higher than that expected from the galactic background abundance, apparently requiring a late-stage seeding of the protosolar molecular cloud core from a nearby supernova. However, numerical simulations of the production, transport, and admixing of freshly synthesized $^{26}$Al in star-forming regions within GMCs (Vasileiadis et al. 2013) indicate that, under typical star formation conditions, the levels of $^{26}$Al in most star-forming regions are comparable to that deduced from CAIs. Thus, the presence of short-lived radionuclides (SLRs) such as $^{26}$Al in the early solar system does not require special circumstances but rather represents a generic feature of the chemical evolution of GMCs.

However, a class of refractory grains and inclusions believed to be temporally related to the formation of canonical CAIs record much lower levels of $^{26}$Al corresponding to initial $^{26}$Al/$^{27}$Al of $<5 \times 10^{-6}$ (Fahey et al. 1987). Of interest are the coarse-grained refractory inclusions with fractionation and unidentified nuclear effects (FUN CAIs; Wasserburg et al. 1977) which, in addition to their low initial abundance of $^{26}$Al, are characterized by large mass-dependent fractionation effects and nucleosynthetic anomalies in several elements. Moreover, the abundance of rare-earth elements and the oxygen isotope...
composition of FUN CAIs indicate that their precursors formed as condensates from a solar gas (Holst et al. 2013). Collectively, these observations are often interpreted as reflecting the formation of FUN CAIs prior to the admixing of stellar-derived $^{26}$Al to the CAI forming gas (Sahijpal & Goswami 1998; Thrane et al. 2008; Makide et al. 2011; Boss & Keiser 2012, 2013, 2014, 2015; Pan et al. 2012). If this interpretation is correct, these objects can be used to track the timing of the addition of $^{26}$Al to the forming protoplanetary disk. Alternatively, the contrasting initial $^{26}$Al abundance of canonical and FUN CAIs may reflect unmixing of two distinct dust components by thermal processing (Trinquier et al. 2009; Paton et al. 2013; Schiller et al. 2015a), namely an old, galactically inherited homogeneous dust component and a new, supernova-derived dust component formed shortly prior to the collapse of the protosolar molecular cloud core. Such a bimodal dust distribution can either be achieved by having separate populations of grains, or having old grains being covered with newly synthesized gas condensates, resulting in a multilayered grain structure. Distinguishing between these two interpretations is critical for understanding the origin and distribution of SLRs in the early solar system.

In this paper, we use GMC-scale adaptive mesh-refinement (AMR) numerical simulations to trace the abundance of $^{26}$Al and $^{60}$Fe in star-forming gas during the early stages of accretion of individual low-mass protostars. We first model the star formation process on the timescale of an evolving GMC structure, and use additional AMR to zoom in on individual stars, allowing us to study the accretion dynamics of individual stars and their disks down to scales of a few astronomical units. This approach allows us, for the first time, to evaluate the level of $^{26}$Al and $^{60}$Fe heterogeneity during the early evolutionary stages of individual protostars that may result from the variable contributions of different supernova sources during the lifetime of the GMC structure. More than 200 stars with masses of at least 0.2 $M_\odot$ form during our simulation, of which we select ten stars that end up having about 1–2 solar masses and one of about 7 solar masses for detailed high-resolution zoom-in investigations. Our models indicate a homogeneous level of $^{26}$Al in the accreting gas for all systems during the first 100 kyr of their formation, although some level of heterogeneity is possible in the later evolutionary stages. Therefore, the contrasting initial $^{26}$Al/$^{27}$Al ratios recorded by canonical and FUN CAIs cannot easily be understood as a result of heterogeneous accretion processes.

2. METHODS

The simulations were carried out with the magnetohydrodynamics (MHD) AMR code RAMSES (Teyssier 2002; Fromang et al. 2006). We solve the equations of MHD using a MUSCL Godunov method with a constrained transport HLLD solver (Miyoshi & Kusano 2005) using a multi-dimensional MonCen slope limiter. To maintain numerical stability in super-sonic flows, and ensure a reasonable time-step, cells where the combined advection and fast-mode speed—the total signal velocity—is above about 150 km s$^{-1}$ are evolved with a more diffusive local Lax–Friedrichs solver. In RAMSES the adaptive mesh is described with a fully threaded oct-tree, and a cell refined to level $n + 1$ has half the linear size compared to a cell refined to level $n$. Refinement can be performed according to a variety of criteria. The basic criterion used in this paper is a Truelove density-based refinement with a factor of four increase in threshold density for each level of refinement, resulting in a constant minimum number of cells per Jeans length (Truelove et al. 1997). This is complemented with a number of refinement criteria based on gradients in density, pressure, and magnetic fields, as described below.

To model a star-forming region, we include self-gravity, cooling parameterized with a table lookup based on Gnedin & Hollon (2012), heating from cosmic rays, and photo-ionization (Osterbrock & Ferland 2006) with a density-dependent exponentially cut-off of 500 cm$^{-3}$ (Franco & Cox 1986). For a more detailed description of the thermodynamics see also Padoan et al. (2015). When the gas reaches a density where a Jeans length at the highest level of refinement is resolved with only a few cells, and several other criteria are fulfilled (see below), sink particles are inserted that interact with the gas through accretion (cf. Padoan et al. 2012, 2014). Sink particles more massive than 8 $M_\odot$ eventually explode as supernovae, with a delay time (stellar life-time) given by a mass-dependent lookup table (Schaller et al. 1992). Fresh SLR material is admixed into the supernova ejecta according to the mass-dependent yields given in (Limongi & Chieffi 2006).

2.1. Set-up and Initial Evolution for a GMC

The current simulation is a partial rerun, with much higher numerical fidelity, of the model in Vasileiadis et al. (2013), which used a (40 pc)$^3$ periodic box with a total mass of $9 \times 10^4 M_\odot$, and a mean magnetic field of 3.5 $\mu$G. The initial evolution was simulated using the unigrid STAGGER-CODE (Kritsuk et al. 2011; Padoan & Nordlund 2011). That model was started up by driving turbulence with a typical root mean square velocity of 6–7 km s$^{-1}$ (Padoan & Nordlund 2011), consistent with Larson’s velocity dispersion-size relation $\sigma (\text{km s}^{-1}) \propto L (\text{pc})^{0.38}$ (Larson 1969, 1981). Self-gravity was then turned on and, subsequently, sufficiently dense gas was converted to a distributions of sink particles, sampled according to a Salpeter initial mass function (IMF) (Padoan & Nordlund 2002). When the kinetic energy feedback due to supernova explosions became significant, the turbulence driving was turned off, and the evolution was continued with the RAMSES code, with a root grid of 128$^3$ and 16 levels of refinement relative to the box size, i.e., with a minimum cell size of about 126 au. Essentially the same star formation recipe as described below was used to self-consistently follow the formation of massive stars, which gradually took over driving from the generation of massive stars originating from IMF sampling. The result is a realistic, evolving GMC model, polluted through supernova explosions with SLRs, and having a mature and diverse population of massive stars (cf. Vasileiadis et al. 2013, for details). Here we repeat parts of that run with 4–6 additional levels of refinement, using an updated version of RAMSES that also provides higher fidelity at a given grid size than the version used by Vasileiadis et al. (2013), by allowing more aggressive choices of Riemann solver and slope limiter. In the current paper we define $t = 0$ as the time of birth of the first massive star formed in the Vasileiadis et al. (2013) RAMSES run.

2.2. Sink Particle Creation and Accretion

Sink particles are used as a subgrid model for stars. Sink particles form from cold gas on the highest refinement level, when it exceeds a certain threshold density, has a convergent
velocity flow, is at a local minimum of the potential, and is at least 30 cells (~3777 au) from any already formed sink particle. In addition, the temperature of the gas has to be below 2000 K. Over time, it is evident that stars form clustered in filaments of high density, in contradiction to the classical model of stars forming isolation due to gravitational collapse (Shu 1977). This is consistent with numerical simulations by other groups (e.g., Hennebelle 2013; Myers et al. 2014; Banerjee & Körtgen 2015) and as seen in observations (Lada & Lada 2003; Bressert et al. 2010). It demonstrates the necessity of using a more complex large-scale zoom-in model, instead of using idealized spherical core-collapse models. The sink particles move through the molecular cloud, accreting gas from surrounding cells within a radius of eight cells from the sink if the total energy in the gas in a nearby cell is negative. The rate of accretion increases gradually from zero at the edge to a fraction of ~0.01 per orbital time near the sink particle, similar to the prescription given in (Padoan et al. 2014). Galilean transformations to the rest frame of a single sink particle make it possible to turn on the built-in RAMSES geometric refinement and keep the particle centered, allowing us to explicitly zoom to the environment around the sinks of interest. The geometric refinement in RAMSES does not force refinement. Instead, it constrains potential refinement only to cells that are located close enough to the sink in order to avoid unnecessary computational costs. We set up geometric refinement in such a way that with decreasing distance from the sink the allowed maximum level of refinement gradually increases. Here we allow refinement in concentric spherical regions with radii of at least 40 cells at each refined level.

Self-gravity in the simulation is accounted for in three steps: first, we compute the potential from only the gas, using it to compute the gravitational force from the gas on the sink particles. Second, we deposit the sink particle masses to the grid using a triangular-shaped cloud method and use the combined potential from the gas and sink particles to compute the gravitational forces on the gas. The gravitational forces between sink particles are accounted for by explicitly using Newton’s law, with a smoothed gravitational potential using a piece-wise polynomial with a softening length of 0.3Δx (Federrath et al. 2010). Particles are evolved with a symplectic kick–drift–kick leap-frog integrator, identical to the one used for dark matter particles in RAMSES. This ensures that close encounters between particles are properly accounted for, and close binaries settle in orbits of ~Δx. To make sure sink particles move in stable orbits we have added two Courant conditions to the maximum velocity and acceleration of the sink particles

\[
\Delta t_r = C_{\Delta} \frac{\min(r_{sv}, \Delta x)}{v}
\]

\[
\Delta t_a = \left[ C_{\Delta} \frac{2}{a} \min(r_{sv}, \Delta x) \right]^{1/2}
\]

where \(C_{\Delta}\) is the Courant number (typically 0.5), \(r_{sv}\) is the minimum distance between two sink particles, \(\Delta x\) is the cell size, \(v\) is the speed of each sink, and \(a\) is the size of the acceleration.

2.3. Zoom-in on Individual Stars

To follow the accretion history of a number of individual stars in detail, while simultaneously retaining realistic initial and boundary conditions of the surrounding medium in the model, we use the method of zoom-in introduced in Nordlund et al. (2014), proceeding in two steps: first, we simulate the evolution of the entire box for approximately 4 Myr with a maximum resolution of 126 au. During this step, several hundred stars of different masses are formed, from which eleven stars are selected. Ten of these stars accrete to from 1 to 2 \(M_\odot\) and one (star 4) accretes to a final mass of about 2.8 \(M_\odot\). In Table 1, we provide an overview of the different sinks. The selected stars are formed—at different points in time and in different environments—from collapsing pre-stellar cores generally located in filamentary structures of the GMC. Our choice of selecting stars that accrete to more than 1 \(M_\odot\) is motivated by the fact that young stars eject a fraction of the accreting mass in strong outflows, which we do not resolve with a resolution of 126 au but (partly) resolve when zooming in. Consequently, in order to model the formation and evolution of what become solar-mass stars, we need to select stars that accrete more than 1 \(M_\odot\) in the first step, i.e., the low resolution run.

In the second step, we rerun the simulation with higher resolution around the selected stars to follow the accretion onto these individual stars in as much detail as we can afford. A compromise between resolution and time coverage allows using up to 20–22 AMR levels of refinement relative to the box size, instead of the 16 levels used in the first step. This corresponds to a minimum cell size of either 8 au (20 levels) or 2 au (22 levels), which still allows following the accretion over about 100 kyr (during which we use output file cadences between 0.2–1 kyr). This is sufficient to cover the periods of time when most of the mass of the stars accretes. To ensure proper coverage of the early phase of star formation, we start most of the second step simulations more than ten thousand years before formation of the selected star, while imposing a “geometric refinement” zoom-in region centered on the pre-stellar core of the star. Simultaneously, we also insert about 10 million tracer particles in a cubic region of about 1.28 \(\times 10^5\) au (0.62 pc) in diameter for eight of the zoom-in runs, namely for stars 1, 5, 6, 7, 8, 9, 10, and 11. The tracer particles are

| # of star | \(\Delta x_{\text{min}}\) in au | \(t_{\text{res}}\) in kyr | \(x\) in pc | \(y\) in pc | \(z\) in pc |
|-----------|-----------------|---------------|-------------|-------------|-------------|
| 1         | 2               | 631           | 33.2        | 30.8        | 7.8         |
| 2         | 2               | 667           | 13.5        | 27.4        | 25.6        |
| 3         | 2               | 1743          | 11.1        | 10.9        | 0.1         |
| 4         | 2               | 2055          | 11.9        | 9.5         | 27.5        |
| 5         | 8               | 2212          | 37.9        | 27.3        | 33.0        |
| 6         | 2               | 2471          | 3.2         | 9.2         | 3.2         |
| 7         | 2               | 2576          | 3.5         | 8.9         | 2.6         |
| 8         | 2               | 2653          | 10.2        | 12.3        | 3.4         |
| 9         | 2               | 3157          | 9.3         | 12.0        | 32.3        |
| 10        | 8               | 3271          | 26.1        | 29.3        | 2.6         |
| 11        | 2               | 3389          | 3.3         | 4.6         | 2.2         |

Note. Column 1: number of star; Column 2: cell size at the highest resolution; Column 3: time of formation of the star in the parental run; Columns 4–6: \(x, y, \) and \(z\)-coordinate of the star at the time of formation.

---

3 In RAMSES, “geometric refinement” is a technique where successively larger regions disallow refinement, one level at a time. Within each region, refinement is allowed, but is not imposed.
distributed with a probability density proportional to mass density, and are passively advected with the gas motion.

Overview of the eleven stars selected for zoom-in. First column: number of star, second column: cell size at the highest resolution, third column: time of formation of the star in the parental run, fourth to sixth column: x, y and z-coordinate of the star at the time of formation.

3. DISTRIBUTION OF SLRS IN SPACE AND TIME ON DIFFERENT SCALES

In this section, we present the distribution of $^{26}$Al and $^{60}$Fe abundance in a GMC, as obtained in our simulations. We present and discuss the evolution and distribution of the SLRs in the entire GMC of $(40 \, pc)^3$ according to our AMR simulation with a maximum resolution of $126 \, au$, which corresponds to a maximum level of refinement of 16 powers of 2 (i.e., $4^{16} = 126 \, au$). In the following, we refer to this run as our parental run. First, we analyze the distribution of the SLRs in the gas phase of the entire GMC and discuss how it affects the abundance in and around the stars. Afterwards, we elaborate in more detail on the SLR abundance around particular stars, by zooming in with a maximum resolution of $2 \, au$ (22 levels of refinement) on nine stars, and with a maximum resolution of $8 \, au$ (20 levels of refinement) around 2 stars. We distinguish between the early (first $\sim 100 \, kyr$ after star formation) and late phase (times later than $\sim 100 \, kyr$).

3.1. Distribution of SLRs in the Gas Phase of the GMC

During the roughly 4 Myr of GMC evolution considered for this paper, nine of the massive stars adopted from the previous STAGGER and RAMSES runs explode as supernovae after their mass-dependent life-times and admix $^{26}$Al as well as $^{60}$Fe at different locations in the GMC.

In Figure 1, we show the average mass-weighted abundance of $^{26}$Al (left panel) and $^{60}$Fe (right panel) as green horizontal lines together with the abundances of the individual stars of masses from 0.2 to 0.5 $M_\odot$ (purple asterisks), 0.5 to 2.5 $M_\odot$ (black asterisks), and 2.5 to 8 $M_\odot$ (yellow asterisks) at their times of formation. The initial abundance of $^{26}$Al and $^{60}$Fe in the cloud prior to the first supernova explosion reflect contributions from earlier supernova events that occurred prior to our $t = 0$. It is clear from Figure 1 that the average $^{26}$Al and $^{60}$Fe abundances in the cloud are highly modulated by supernova events (illustrated by the blue stars on top of the plots), followed by a gradual decrease due to radioactive decay. The first supernovae corresponds to a star of $13 M_\odot$ and result in a significant enhancement of the $^{26}$Al abundance relative to $^{60}$Fe. There are two reasons for this. First, $^{26}$Al ($\tau_{1/2}^{Al} \approx 717 \, kyr$) decays about three times faster than $^{60}$Fe ($\tau_{1/2}^{Fe} \approx 2.6 \, Myr$; Rugel et al. 2009) and, hence, the $^{60}$Fe abundance is depleted less than $^{26}$Al before the first supernova event. Second, the first supernova event is not a very massive star, which produces $^{60}$Fe per unit less mass relative to more massive supernovae. The second supernova explodes with a mass of $22 M_\odot$, less than 200 $klyr$ later and significantly enriches the cloud in $^{60}$Fe as it is more efficient in producing $^{60}$Fe than the first supernova. During the time until the next supernova explosion, one can clearly recognize the characteristic decay of both SLRs before the box becomes efficiently enriched in SLRs by the third supernova. This supernova is the most massive one during the entire evolution of the GMC with $75 M_\odot$ and is thus particularly responsible for the enhancement in $^{60}$Fe. The subsequent supernovae, with masses of $15 M_\odot$, $29 M_\odot$, $40 M_\odot$, $13 M_\odot$, $22 M_\odot$, and $29 M_\odot$ do not enhance the average abundance as much, partly because enrichments of the already enhanced GMC appear less significant on the logarithmic scale.

In general, we can see an overall increase of SLR abundances (ranging from about $2.5 \times 10^{-6}$ to about $1 \times 10^{-4}$ for $^{26}$Al/$^{27}$Al and from about $5 \times 10^{-7}$ to about $7 \times 10^{-6}$ in $^{60}$Fe) over time, consistent with earlier results of Vasileiadis et al. (2013).

Enrichment in SLR abundances is also reflected in the spatial distributions of SLRs at different times. The two left panels of Figure 2 show the distribution of $^{26}$Al/$^{27}$Al in the cloud for all cells with respect to density and temperature for two different times. The left panel illustrates the distribution just at the end of the quiescent period at $t = 2.2 \, Myr$, while the middle panel corresponds to the end of the simulation. In both diagrams one can see that the temperature of the gas decreases with increasing density. Also, the spread in $^{26}$Al/$^{27}$Al is wider for low density gas than for high density gas. Both diagrams reveal that the highest abundances occur for highest temperatures but, due to several recent supernova enrichments, this property is much more evident at the end of the simulation (middle panel) than after the supernova quiet phase (left panel). The significant number of cells with high temperatures and low density reveals the admixing of enriched gas from supernova explosions into the GMC. To illustrate the spatial distribution of the SLRs, in particular $^{26}$Al/$^{27}$Al, we present the distribution of $^{26}$Al/$^{27}$Al inside our entire box with the visualization software VAPOR (Clyne et al. 2007). The color scheme represents $^{26}$Al/$^{27}$Al.
Figure 2. Distribution of $^{26}$Al/$^{27}$Al abundance inside the entire box of all the cells just at the end of the supernova quiet period at $t = 2.2$ Myr (left panel) and at the end of the simulation $t = 3.9$ Myr (middle panel) with dependence on their density. The colors in the diagram represent the gas temperature from cold (purple) to warm (red). The right panel illustrates how $^{26}$Al/$^{27}$Al is distributed in the GMC at the end of the simulation. White represents low abundances ($10^{-5}$), while purple represents high abundances ($10^{-2}$).

Figure 3. The two panels illustrate the probability distribution of SLR values in logarithmic steps of 0.1 at times briefly after the formation of star 1 and 2, star 3, star 5, star 6, star 7, stars 8 and 9, and at the end of the simulation. We have omitted star 4 in these histograms for clarity. Note that the histograms for star 4 are similar to those of stars 3 and 5. Left panel: $^{26}$Al/$^{56}$Fe; right panel $^{60}$Fe/$^{56}$Fe.

To quantify the distribution of SLR abundances in our GMC at different times more accurately, we plot the $^{26}$Al/$^{27}$Al and $^{60}$Fe/$^{56}$Fe distribution in the form of histograms in Figure 3. The distributions clearly show that large spatial heterogeneities in $^{26}$Al/$^{27}$Al abundance exist throughout the entire GMC due to supernova enrichments. The SLR ratios cover a range of up to six orders of magnitude for $^{26}$Al/$^{27}$Al and up to about four orders of magnitude for $^{60}$Fe/$^{56}$Fe at times not too long after recent supernova events. Furthermore, the distribution is narrower and the GMC lacks very high values of SLRs at the end of more quiescent periods (blue solid line, red dotted line). Comparing the histogram for $t = 2.229$ Myr, corresponding to the end of a quiescent period, with the distribution shortly after the two first supernova enrichments at $t = 0.679$ Myr shows that the maximum SLR values are about two orders of magnitude lower as seen in Figure 2. This significant decrease in $^{26}$Al and $^{60}$Fe abundance observed at the end of the quiescent period cannot be explained by radioactive decay and, instead, must reflect progressive admixing of the SLR enriched high density gas with lower, lower density gas present in the GMC. Considering the range of abundances found in our model, both the canonical value measured in bulk CAIs from Carbonaceous chondrites of Vigarano type (CV CAIs) as well as lower values measured in FUN CAIs are well represented within the range found in our simulation, although the majority of star-forming gas is of lower abundance.

Similarly to Figure 1, we illustrate in Figure 4 (left panel) the evolution of the average $^{60}$Fe/$^{26}$Al ratio in the GMC together with the abundances of the individual stars at their time of formation (asterisks) and the exploding supernovae. Although the average ratios vary due to the different decay times of $^{60}$Fe and $^{26}$Al as well as the different supernova enrichments during the evolution of the GMC, the value generally decreases from about 0.3 to about 0.16 at the end of the simulation due to the larger amount of supernovae that admix more $^{26}$Al than $^{60}$Fe into the GMC. Again, this value is in agreement with Vasilieaidis et al. (2013), who found an average value of about 0.2. Furthermore, the value at later times is also consistent with the galactic value of $0.15 \pm 0.06$ (Diehl et al. 2006; Wang et al. 2007). Our average value is higher than the galactic value throughout the entire evolution of about 4 Myr, but could eventually have become lower, if we had continued the simulation for a longer time. Despite natural fluctuations of the $^{60}$Fe/$^{26}$Al value, the overall trend of a decrease is expected, since supernovae generally admix less Fe relative to Al for decreasing masses of the progenitor, and therefore the $^{60}$Fe/$^{26}$Al in GMCs will tend to decrease...
over time. This argument is also supported by the changing distribution of $^{60}\text{Fe}/^{26}\text{Al}$ ratios inside our cloud Figure 4 (right panel). Since our GMC has already evolved long enough before the start of our simulation, the less massive supernova already occurs at the beginning of our simulation. Although somewhat counter-intuitive, the associated distribution (black solid line) reveals that the lowest $^{60}\text{Fe}/^{26}\text{Al}$ ratios occur after a low-mass supernova. In general, however, the early SLR abundances are predominantly dominated by enrichments of short-lived heavy supernovae, while longer-lived low-mass supernovae mostly occur at later times and cause new enrichment. At this point, we emphasize the difficulties of measuring and estimating one single $^{60}\text{Fe}/^{26}\text{Al}$ value for a GMC considering the large range of $^{60}\text{Fe}/^{26}\text{Al}$ ratios reflected in Figures 3 and 4 (right panel) present throughout the entire GMC. Although mixing occurs inside the GMC, fluctuations are still significant indicating that the process of mixing occurs on longer timescales relative to that depicted in our simulations.

To better understand the heterogeneities inside the GMC, we compare the timescales that are relevant for mixing of the SLRs. The dynamical crossing time is

$$t_{\text{cross}} = \frac{l}{\mathcal{M}c_s},$$

where $l = L_{\text{box}}/2$ is a characteristic length and $\mathcal{M}c_s = 6\sim7 \text{ km s}^{-1}$ is the typical turbulent rms speed. This gives a mixing time of $t_{\text{cross}} \sim 3 \text{ Myr}$. Another relevant timescale is the cooling time of the hot medium

$$t_{\text{cool}} = \frac{3k_bT}{2n\Lambda},$$

where $\Lambda$ is the cooling rate. If we assume approximate pressure equilibrium between different phases, then hot gas has a vastly different density compared to cold gas, and it has to be cooled down and compact to efficiently mix with the cold gas. In our case the cooling time can be calculated to be $\sim1 \text{ Myr}$ for $10^6 \text{ K}$ gas. The average time between different supernovae $t_{\Delta SN}$ provides the time between supernova enrichments. Given that nine supernova explosions occurred in roughly 4 Myr during our simulation, we set $t_{\Delta SN}$ to 450 kyr. This is significantly lower than either the crossing time or the cooling time, which explains the heterogeneous SLR abundance in the gas of the GMC.

### 3.2. Abundance of SLRs in Stars

After having shown that SLR abundances of the gas are heterogeneous, we investigate to what extent the heterogeneity is present in the stars (represented by the asterisks in Figure 1). Altogether 252 stars of masses higher than $0.2M_\odot$ form between $t=0$ and the end of the simulation, of which 46 evolve to masses higher than $8M_\odot$ and will end their lives in supernova explosions. As mentioned earlier, none of these stars has exploded in a supernova event by the end of the simulations. The GMC also contains lower mass stars, but we exclude stars of masses lower than $0.2M_\odot$ because the minimum cell size of 126 au is not sufficient to properly sample the tail of the turbulence and resolve the cores of lower mass stars. As we are mostly interested in the evolution of solar-mass stars and due to the lack of radiative transfer, we also exclude the high mass stars for our analysis and only focus on the 206 stars in the range of $0.2M_\odot$ to $8M_\odot$. In agreement with Vasileiadis et al. (2013) and Gounelle et al. (2009), the stars show different relative abundances in $^{26}\text{Al}$ (varying from about $1 \times 10^{-7}$ up to about $1 \times 10^{-5}$), as well as in $^{60}\text{Fe}$ (varying from about $1 \times 10^{-7}$ up to $3 \times 10^{-6}$) at their time of formation. Moreover, similar to the distribution of all the gas in the cloud, the initial abundances are on average lower and show a narrower spread in abundance than seen at later times. However, there are significant differences in the overall distributions of SLR abundances between the gas and the stars. The stars show a smaller range of abundances than the gas and the stars have abundances that always lie below the average abundance in the gas at that time. Moreover, a significant number of stars show abundances that follow the decay curve of the average value of the gas at the very beginning of the simulation (the barely visible small green lines). We interpret this result such that these stars formed from a first rather old gas reservoir. The parental run does not include tracer particles, which would have allowed us to track the history of the gas from at least one supernova enrichment during the evolution of the GMC. Nevertheless, we can use the decay time of the SLRs as a clock to draw some qualitative conclusions about the origin of the gas in stars. In agreement with the delay of enriched SLR abundances for the stars in our box, we suggest that although highly SLR enriched gas from supernovae is present in the GMC, it does not contribute to the formation of stars until at least several 100 kyr later. This is in agreement with results from Vasileiadis et al. (2013), who followed the motion of gas injected by supernovae by using tracer particles and estimated that it takes of the order of 1 Myr until such gas is incorporated in star-forming cores. Observations show that
stars form in regions of cold, dense gas. Hence it is obvious that the gas in supernova ejecta needs time to cool before it can take part in star formation. This is in agreement with the results seen in Figure 2 (left and middle panels), as well as in Figure 3. In general, the gas covers a large range of ratios and densities. However, $^{26}\text{Al}/^{27}\text{Al}$ abundances higher than $10^{-3}$ only occur for densities that are lower than $10^{-15}$ g cm$^{-3}$ and, thus, cannot yet contribute to star formation. The plot shows that only a small fraction of the cells have densities higher than $10^{-16}$ g cm$^{-3}$; these cells correspond to potential star-forming cores. Also, the gas does not show such large spreads in the $^{26}\text{Al}/^{27}\text{Al}$ ratio as for lower densities. Considering that the densities of the star-forming cores are several orders of magnitude higher than the SLR enriched gas in the vicinity of recent supernovae, this indicates the difficulty of contaminating the star-forming cores with new gas of different abundance. Given that high abundances must be associated with recent supernova activities, we conclude that the gas needs time to cool sufficiently before it is able to clump and subsequently to form stars only from the gas with lower SLR ratios.

3.3. SLR Distribution in the Vicinity of Stars at Early Times

With respect to the measured differences in $^{26}\text{Al}/^{27}\text{Al}$ between canonical CAIs and FUN CAIs of more than one order of magnitude, it is of particular interest to investigate whether such differences occur during the accretion process. It is generally accepted that the formation of CAIs (both CV and FUN types) is restricted to the very early phase of star formation and very close to the star, probably only to the first few thousand years and the inner astronomical units (Krot et al. 2009; Holst et al. 2013). Since the resolution around the stars is 126 au and the time between snapshots in the parental run already is 50 kyr, we cannot resolve the surrounding to this level for all the stars in our simulation. However, late-stage contamination of an accreting star by freshly synthesized supernova material requires that the differences in abundance originate at distances far beyond the sizes of star-forming cores. Therefore, we test whether significant differences in abundance occur within 5000 au of the star 50 kyr after its formation. In Figure 5, we show the mass-weighted distribution around the stars in the mass range of 0.2 $M_\odot$–8 $M_\odot$ that show ten times higher $^{26}\text{Al}/^{27}\text{Al}$ ratios within a distance of 5000 au and less than 50 kyr after the birth of the star with respect to the abundance in the corresponding star. Altogether only nine of the 206 stars show contaminations of more than a factor of ten, among them only two stars with masses higher than 1 $M_\odot$. We emphasize that all of the cells with very different abundance are at least 1500 au away from the star and belong to times already up to 50 kyr after the star has formed. Hence, we do not see any contaminations at early times relevant for CAI formation ($t < 0.1$ kyr) that can account for the measured differences of $^{26}\text{Al}/^{27}\text{Al}$ in FUN and canonical CAIs.

To ensure that this result is robust, we selected a few stars to follow their formation phase with higher resolution. The eleven stars selected for zoom-in are marked with red circles in Figure 1. Ten of the eleven stars accreted between 1 and 2 $M_\odot$. Additionally, we also modeled one star that accreted to more than 2.8 $M_\odot$. Figures 6 and 7 show the temporal evolution of the average $^{26}\text{Al}/^{27}\text{Al}$ ratio and $^{60}\text{Fe}/^{56}\text{Fe}$ in spherical shells at distances of 10 and 1000 au as well as their standard deviations for the selected stars. These have different relative abundances of $^{26}\text{Al}/^{27}\text{Al}$ between $10^{-7}$ and $2 \times 10^{-6}$, while $^{60}\text{Fe}/^{56}\text{Fe}$ ratios are between $10^{-7}$ and $8 \times 10^{-7}$. Although the stars selected for zoom-ins show abundances below the canonical value of $5 \times 10^{-5}$, we emphasize that our selection is valid to test the hypothesis of $^{26}\text{Al}$ enrichment in the solar system through supernovae. Considering that bulk CV CAIs are supposed to reflect $^{26}\text{Al}$ enrichment after solar birth, the initial abundances in our selected stars are consistent with values less than $3 \times 10^{-6}$ as measured in FUN CAIs. Since these values are considered to reflect the original abundance in the collapsing pre-solar core, and due to the fact that higher abundances are available in the GMC, our selection provides an adequate sample to test the enrichment hypothesis.

As expected from the results obtained using the parental run, the average $^{26}\text{Al}/^{27}\text{Al}$ and $^{60}\text{Fe}/^{56}\text{Fe}$ ratios are almost indistinguishable at different distances from the parent stars (left and right upper panel of Figures 6 and 7). This suggests a spatially homogeneous distribution of $^{26}\text{Al}$ and $^{60}\text{Fe}$ within 1000 au during the accretion process for the first 100 kyr of evolution. We note that the apparent time integrated variability is consistent with the typical decay curve for $^{26}\text{Al}$ and $^{60}\text{Fe}$. In principle, inflow of gas with different SLR abundances at two different locations and identical in-fall speeds could nevertheless cause spatial heterogeneities without affecting the average SLR value, which would be reflected in large deviations from the mean value. However, the ratios deviate only marginally from the average values in the shells as illustrated by plotting the standard deviation from the mean value at distances of 50 au and 1000 au in the lower panels of Figures 6 and 7. Generally, the different stars all have deviations that range from less than 1 % to at most 20% of the mean value. Importantly, the fluctuation observed in the star with the largest fluctuation in $^{26}\text{Al}/^{27}\text{Al}$ ratios (star 9) is still lower by more than one order of magnitude relative to the difference between canonical and FUN CAIs.

To better understand the reason for the spatial homogeneity of $^{26}\text{Al}$ during the accretion, we investigated the origin of the gas and compared it with the SLR distribution at time $t = 0$. The right panels of Figures 8 and 9 illustrate the $^{26}\text{Al}/^{27}\text{Al}$ distribution of all cells within a distance of 100 kau around the stars at time $t = 0$ for the eight zoom runs including tracer particles. As indicated by Figure 6, the gas does not show spreads of more than a factor of five in $^{26}\text{Al}/^{27}\text{Al}$ abundance within about 10 kau at the time of stellar birth. In contrast, the gas distribution beyond $\sim 10^4$ au can be of very different abundance, but it is also of much lower density. When
following the motion of the gas with tracer particles, we find
that—for at least the first 50 kyr—all of the gas within the inner
100 au was located less than 10 kau away from the star at stellar
birth. Considering the narrow spread in SLR abundances for
the inner several thousand astronomical units at the time of star
formation, this explains why we only see small differences in
SLR distribution during the early accretion process of the stars.
In Figure 10, we show the same phase diagrams as in the right
panels of Figures 8 and 9, but coloring the temperature instead
of the density of the gas. Densities decrease with increasing
distance from the star and moreover the gas close to the star is
of low temperature. This in agreement with observations that
stars form from cores of cold gas of about \( \sim 10 \) kau in size
(Enoch et al. 2007).

Our results indicate that heterogeneous accretion processes
cannot account for the variability in the \( ^{26}\text{Al}/^{27}\text{Al} \) ratios
between canonical and FUN CAIs during the early stages of star formation, which may appear counter-intuitive considering the variability of several orders of magnitude in SLR abundances present within the entire GMC. We consider below the cascade of events leading to star formation in a GMC to better understand our results. Turbulent motions inside GMCs predominantly cause the formation of filaments of parsec-size inside GMCs. Inside these filaments gas becomes further compressed to form pre-stellar cores of sizes of 5–10 kau consistent with theoretical predictions of a

Figure 8. Original location of gas at time of stellar formation, located within a distance of 100 au from star 1 (top left), star 5 (second row left), star 6 (third row left), and star 7 (bottom left) at times indicated in the plots. The distances on the x-axis refer to the positions of the gas at the time of star formation. The right panels illustrate the $^{26}$Al/$^{27}$Al distribution in the gas around the star at the time of its birth.
Bonnor–Ebert sphere. Eventually, the cores become dense enough to overcome the threshold value for gravitational collapse and they collapse to stars. Compared to typical sizes of GMCs, pre-stellar cores are about three orders of magnitude smaller and fill only a small part of the GMC (Figure 2). In order to contaminate a pre-stellar core during formation, it has to be near the boundary between two regions with different SLR abundances. Nevertheless, we consider the hypothetical case of a pre-stellar core that is located close to such a large difference boundary. Then we are likely to have the following two regimes: on the one hand, densities inside pre-stellar cores are very high compared to the average in the

Figure 9. Same as Figure 8, but for stars 8, 9, 10, and 11.
rest of the GMC; on the other hand, SLR enriched gas is associated with recent supernova events and therefore located in regions of warm gas, and particularly of low density (right panels of Figures 8–10). Thus, even if the gas that is in the vicinity of the pre-stellar core has a significantly different abundance, it is difficult for that gas to penetrate the core because of the large density contrast.

Although our simulations have not identified the existence of appreciable spatial and/or temporal heterogeneity in SLR abundances during the early accretion phases, we consider also the possibility that a pre-stellar core is contaminated by enriched gas at the beginning of its existence when the densities are still rather low. Similarly to our analysis in the previous section for the mixing on GMC scales, we compare the relevant timescales for the mixing at the scale of pre-stellar cores, which is the life-time of a pre-stellar core with the crossing time of the gas. Observational constraints suggest that the life-times of pre-stellar cores range from 100 kyr up to 500 kyr (Enoch et al. 2008). As stars form in regions of cold gas of mostly molecular hydrogen, we adopt a value of 10 K for the temperature of the sound speed. Considering radii of pre-stellar cores of about 5–10 kau for a solar-mass star, we obtain crossing times of about 100–250 kyr, similar to the life-times of pre-stellar cores, which could in principle allow for insufficient mixing inside the core. However, our results show only modest variations in SLR ratios and thus we conclude that the cold gas is already well mixed before the formation of the star-forming cores. Even if a potential contamination occurs, it only contributes slightly to the abundance per mass and only penetrates the outer edge of the core, from where it takes often more than 100 kyr for the gas to fall in toward the star (left panels of Figures 8–10).

Figure 10. Same as right panel in Figures 8 and 9, but showing temperature instead of density from left to right and to bottom for stars 1, 5, 6, 7, 8, 9, 10, 11, and additionally 2. Only cells with $^{26}\text{Al}/^{27}\text{Al}$ ratios below $10^{-2}$ are illustrated. The lower/upper cut-off value for the temperature is 10/1000 K and values below/above that value are colored purple/red.
3.4. Late Phase: Potential Heterogeneity of SLRs at Later Times

Although we do not detect any significant differences in $^{26}\text{Al}/^{27}\text{Al}$ at early times, the fact that gas from initial distances beyond 10 kau accretes to the star over timescales $>100$ kyr allows for the possibility of contaminations at later times. Therefore, we consider the evolution of the stellar surroundings, including the protoplanetary disks, at a phase later than the initial $\approx 100$ kyr, which we refer to as the “late phase” for simplicity. Due to high computational costs, only data for three stars (star 2, 3, and 4) were acquired for the late phase and none of these runs include tracer particles. One of these stars shows enhancements of up to a factor of 2 in $^{26}\text{Al}/^{27}\text{Al}$ within a distance of only 10 au from the star after about 160 kyr (Figure 11). Such contaminations at later times are possible due to massive accretion of mass onto the young star during the early phase, which causes a decrease in density around the star. Hence, it becomes possible for material that was not initially bound to the protostar to approach the vicinity of the star at later times. Unfortunately, we do not have data from simulations including tracer particles for this run, with which we could analyze the origin of the gas causing the enrichments. We point out that this late pollution is different from the idea of supernovae that occurred at the beginning of the simulation, in agreement with the increase of the average $^{26}\text{Al}/^{27}\text{Al}$ in the gas phase, and consistent with the findings in Vasileiadis et al. (2013) that the average abundance of $^{26}\text{Al}/^{27}\text{Al}$ for the star-forming gas increases at later times. Thus, later times of GMC evolution are more favorable for larger variabilities in SLR ratios around stars. Nevertheless, we do not detect any significant contaminations that could account for differences in $^{26}\text{Al}/^{27}\text{Al}$ of more than one order of magnitude for any of the more than 200 stars considered in this study. This suggests that the measured heterogeneities in $^{26}\text{Al}/^{27}\text{Al}$ between canonical and FUN CAIs are caused by a different mechanism than supernova contamination.

4. ORIGIN OF THE VARIABILITY IN THE $^{26}\text{Al}/^{27}\text{Al}$ RATIO BETWEEN CANONICAL AND FUN CAIS

As indicated by the radioactive decay of the SLRs, and the initial average abundance in the gas phase, most of the stars seem to have formed from the initial gas reservoir present in the GMC. Toward the end of the run more and more stars that potentially could have ended as solar-mass stars formed from SLR enriched gas and the spread in SLR abundances seems to be higher among the stars than at the beginning of our simulation (Figure 1 and left/middle panels of Figure 2). In contrast, it appears that the average SLR abundance in the gas reservoir that contributes to star formation is generally enhanced after 3.7 Myr and the spread again becomes narrower. This general enrichment of the reservoir stems from supernovae that occurred at the beginning of the simulation, in agreement with the increase of the average $^{26}\text{Al}/^{27}\text{Al}$ in the gas phase, and consistent with the findings in Vasileiadis et al. (2013) that the average abundance of $^{26}\text{Al}/^{27}\text{Al}$ for the star-forming gas increases at later times. Thus, later times of GMC evolution are more favorable for larger variabilities in SLR ratios around stars. Nevertheless, we do not detect any significant contaminations that could account for differences in $^{26}\text{Al}/^{27}\text{Al}$ of more than one order of magnitude for any of the more than 200 stars considered in this study. This suggests that the measured heterogeneities in $^{26}\text{Al}/^{27}\text{Al}$ between canonical and FUN CAIs are caused by a different mechanism than supernova contamination.
contrasting initial $^{26}$Al/$^{27}$Al ratios observed between the FUN and canonical CAIs, which appears unrealistic.

One might argue that CAIs formed instead around stars lower than 0.2 $M_\odot$ in mass, which are closer to the star. Even with our state-of-the-art zoom-run, we do not resolve the formation of these very low-mass stars properly and we do not have a reliable statistics for these stars. However, we are confident that the SLR to distance relation would not be very different for low-mass stars, considering that these stars formed from the same gas reservoir as the higher mass stars. Taking additionally into account the uncertainty whether CAIs can travel through the ISM and accrete onto foreign star–disk systems, we consider this scenario to be unlikely.

4.2. Thermal Processing of Dust Grains

Instead, we argue that measured differences in CAIs and chondrules are most likely caused by physical processes neglected in our simulation. In our model, we only considered the motion of the gas to evaluate the influence from GMC scales down to protoplanetary disk scales. However, observations show that GMCs and protoplanetary disks consist of about 1% of dust. Therefore, we suggest that the contrasting initial $^{26}$Al/$^{27}$Al values recorded by canonical and FUN CAIs reflect unmixing of the $^{26}$Al carrier by thermal processing during the early stage of solar system formation. This is supported by the observation that FUN CAIs plot on the solar system nucleosynthetic correlation line defined by inner solar system solids, asteroids, and planets (Schiller et al. 2015a). Although a detailed study of thermal processing is beyond the scope of this paper, we discuss the basics of the process here.

Consider the evaporation time

$$I_{ev} \propto \nu^{-1} e^{\frac{k_B}{\kappa T}}$$

(5)

(Tielens & Allamandola 1987; Boogert et al. 2015), where $\nu$ is the vibrational frequency, $E_B$ the binding energy of the dust grain, $k_B$ the Boltzmann constant, and $T$ the temperature. Approximating dust grains to be perfectly spherical, the energy of one photon $h\nu$, where $h$ is the Planck constant, is assumed to scale with the inverse of the volume of the grains. Thus, we obtain

$$I_{ev} \propto \mu^3 e^{\frac{k_B}{h\nu}}.$$  

(6)

The dust composition in the ISM consists of grains of different size (up to micrometer size) and different age. Due to radioactive decay, older dust grains are considered to show lower SLR abundances than younger grains. Taking additionally into account that older grains were exposed to potentially destructive radiation for a longer time, the surviving grains have higher binding energies and/or larger grain sizes than the younger grains. Furthermore, older components and thus SLR depleted components are more likely to be in the central layers of the grains, whereas younger components are more likely to accumulate on the surface of the grains. Thus the younger grain components generally

1. vaporize at lower temperatures,
2. are considered to be in smaller grains and,
3. shield the older components from radiation.

During the star-forming process, the well mixed dust grains in the pre-stellar core fall in toward the star, where they are exposed to stellar radiation. Since the younger, SLR enriched components vaporize more easily, the gas phase can become locally enriched in SLRs. Depending on the temporally changing strength of irradiation, more or fewer layers of the dust grains are vaporized, eventually causing a continuous distribution of different $^{26}$Al/$^{27}$Al ratios in the gas around the star. Due to the short timescales of this collapsing phase, of the order of kyr or less, the gas cannot mix to a homogeneous reservoir before CAIs are formed by condensation out of the gas phase. In this way, CAIs inherit the thermally induced, local heterogeneities of $^{26}$Al/$^{27}$Al ratios in the early gas phase.

Progressive thermal processing of in-falling $^{26}$Al-rich molecular cloud material in the inner solar system has also been invoked to account for the large-scale heterogeneity in $^{26}$Al that existed at the time of accretion of most asteroidal bodies (Trinquier et al. 2009; Larsen et al. 2011; Paton et al. 2013; Schiller et al. 2015a, 2015b; van Kooten et al. 2016). We note that the initial $^{60}$Fe abundance for stars in our simulations is much higher than that inferred for the early solar system based on differentiated meteorites and chondritic components (Tang & Dauphas 2012, 2015). Similarly to Vasileiadis et al. (2013), we interpret this discrepancy as reflecting efficient removal of $^{60}$Fe from disk solids via thermal processing of their precursors, which requires that the carrier phase of $^{60}$Fe was significantly more volatile than the $^{26}$Al carrier. As such, inferred initial $^{60}$Fe estimates based on meteoritic material such as differentiated meteorites and/or chondrules may not be representative of that of the bulk solar system.

5. CONCLUSIONS

For the first time, we followed the dynamics of GMC gas down to the small scales relevant for individual star and protoplanetary disk formation, while we simultaneously...
accounted for the large-scale effects induced by supernovae, magnetic fields, and turbulence in the GMC. In particular, we analyzed the abundance of the $^{26}$Al and $^{56}$Fe SLRs around newly formed stars in simulations of a (40 pc)$^3$ GMC carried out with the AMR code RAMSES. First, we simulated the dynamics in the GMC including enrichments from supernovae with a highest resolution of 126 au for about 4 Myr. During this time, more than 200 stars with masses in the range of $0.2 M_\odot$–$8 M_\odot$ formed inside the GMC. To model the gas dynamics in the early phases of star formation in further detail, we investigated the distribution of the $^{26}$Al/$^{27}$Al ratio during the first ~100 kyr for eleven of the stars, by renuning their formation and early evolution phases with higher spatial resolution, using grid sizes down to 2 au. We conclude from our simulations that huge variations in abundance ratios of $^{26}$Al/$^{27}$Al and $^{56}$Fe generated by supernova explosions exist in GMCs. However, highly enhanced values only occur in the hot, low density gas located close to recent supernova events. Over time, the ejecta are cooled down and are incorporated into star-forming gas. Here the gas becomes mixed, such that the variations in the cold dense gas are modest. None of the more than 200 stars showed abundances variations of a magnitude that could have accounted for the measured differences between canonical CAIs and FUN CAIs. Considering that we only see marginal deviations from the characteristic decay curve of the initial SLR abundance for the gas around the stars selected for zoom-ins, we conclude that the gas in pre-stellar cores is already well mixed before the formation of the stars. We demonstrated that the gas forming the star–disk system accretes from distances within about 10$^4$ au, which is in agreement with observations and theoretical predictions for the size of a Bonnor–Ebert sphere for a $1 M_\odot$ star. The collapsing gas in the core that forms the star is gravitationally bound and by definition overdense compared to its surrounding. Thus, hot gas from recent supernovae cannot easily pollute the stellar environment in the early phases corresponding to stage 0/1, when the star still has a massive envelope and is strongly accreting from its initial gas reservoir.

However, we point out that the situation changes for times later than about 100 kyr, when most of the surrounding gas has accreted onto the star–disk system and the density of the envelope has dropped by a few orders of magnitude. At these times, gas with different abundance can penetrate the environment around the star and might potentially lead to significant variability of the SLR abundances in the protoplanetary disk. As in previous models these variations are related to the production of SLRs by supernovae, but the picture is different in the sense that the SLR enrichments already occur in cold gas. In contrast to a specific injection into the star–disk system, the star moves through the interstellar medium and eventually enters gas reservoirs of different SLR composition. Therefore, the traditional model of supernova injection is also misleading at later times in star formation.

Instead of being caused by early heterogeneities in the SLR distribution in the gas phase around young stars, we suggest thermal processing of the dust components as the main explanation for the differences in $^{26}$Al/$^{27}$Al ratios between canonical CAIs and FUN CAIs. The main point is that new and old dust are likely to differ both in binding energies and distribution over grain size, with the fraction of new dust being larger in small dust grains, which also are expected to have, on average, smaller binding energies. The old dust component has been—perhaps even repeatedly—subjected to the harsh conditions in the interstellar medium, and what still remains intact is thus expected to be the fraction with the highest binding energies.

During the early phase of star formation, the temperature and pressure distributions near the star are likely to populate the regime where refractory solids can form, but these conditions are likely changing on timescales of thousands of years or fewer. Moreover, the precursor mix of gas and dust will take different—and possibly complex—paths through the protoplanetary disk, subjecting it to varying temperatures and pressures. Thus, different fractions of “new” and “old” dust will vaporize under varying conditions during the formation process, allowing variable SLR abundance patterns in the gas out of which CAIs form. Such a mechanism can not only explain the large differences in abundances between canonical and FUN CAIs, but also the continuous and broad distribution of $^{26}$Al/$^{27}$Al measured among FUN CAIs (Park et al. 2013). Because the old dust component, with its high binding energy, is expected to be most resilient to heating, the proposed mechanism is also consistent with the findings by Makide et al. (2009) that CAIs that contain high temperature minerals such as grossite and hibonite present in Carbonaceous chondrites of Renazzo type (CR chondrites) formed with a low initial abundance of $^{26}$Al.

This research was supported by a grant from the Danish Council for Independent Research to A.N., a Sapere Aude Starting Grant from the Danish Council for Independent Research to T.H., and by the European Research Council (ERC) under the EU Horizon 2020 research and innovation programme (grant agreement No 616027) through ERC Consolidator Grant “STARDUST2ASTERROIDS” to M.B. Research at the Centre for Star and Planet Formation is funded by the Danish National Research Foundation (DNRF97). We acknowledge PRACE for awarding us access to the computing resource CURIE based in France at CEA for carrying out part of the simulations. Archival storage and computing nodes at the University of Copenhagen HPC center, funded with a research grant (VKR023406) from Villum Fonden, were used for carrying out part of the simulations and the post-processing. Finally, we acknowledge the developers of the python-based analyzing tool yt (http://yt-project.org/) (Turk et al. 2011) that simplified our analysis.

REFERENCES

Banerjee, R., & Körtgen, B. 2015, arXiv:1509.03436
Bash, F. N., Green, E., & Peters, W. L., III 1977, ApJ, 217, 464
Blitz, L., & Shu, F. H. 1980, ApJ, 238, 148
Boogert, A. C. A., Gerakines, P. A., & Whittet, D. C. B. 2015, ARA&A, 53, 543
Boss, A. P., & Keiser, S. A. 2012, ApJL, 756, L9
Boss, A. P., & Keiser, S. A. 2013, ApJ, 770, 51
Boss, A. P., & Keiser, S. A. 2014, ApJ, 788, 20
Boss, A. P., & Keiser, S. A. 2015, ApJ, 809, 103
Bressert, E., Bastian, N., Gutermuth, R., et al. 2010, MNras, 409, L54
Clyne, J., Mininni, P., Norton, A., & Rast, M. 2007, NJPh, 9, 301
Connelly, J. N., Bizzarro, M., Kot, A. N., et al. 2012, Sci, 338, 651
Diehl, R., Halloin, H., Kretschmer, K., et al. 2006, Natur, 439, 45
Dobbs, C. L., Krumholz, M. R., Ballesteros-Paredes, J., et al. 2014, in Protostars and Planets VI, ed. R. S. Klessen, C. P. Dullemond, & T. Henning (Tucson, AZ: Univ. Arizona Press)
Ebel, D. S., & Grossman, L. 2000, GeCoA, 64, 339
Enoch, M. L., Evans, N. J., II, Sargent, A. I., et al. 2008, ApJ, 684, 1240
Enoch, M. L., Glenn, J., Evans, N. J., II et al. 2007, ApJ, 666, 982
