Supernova enrichment and dynamical histories of solar-type stars in clusters

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ABSTRACT
We use N-body simulations of star cluster evolution to explore the hypothesis that short-lived radioactive isotopes found in meteorites, such as 26Al, were delivered to the Sun’s protoplanetary disc from a supernova at the epoch of Solar system formation. We cover a range of star cluster formation parameter space and model both clusters with primordial substructure and those with smooth profiles. We also adopt different initial virial ratios – from cool, collapsing clusters to warm, expanding associations. In each cluster, we place the same stellar population; the clusters each have 2100 stars and contain one massive 25 M⊙ star which is expected to explode as a supernova at about 6.6 Myr. We determine the number of solar (G)-type stars that are within 0.1–0.3 pc of the 25 M⊙ star at the time of the supernova, which is the distance required to enrich the protoplanetary disc with the 26Al abundances found in meteorites. We then determine how many of these G-dwarfs are unperturbed ‘singletons’; stars which are never in close binaries, nor suffer sub-100 au encounters, and which also do not suffer strong dynamical perturbations. The evolution of a suite of 20 initially identical clusters is highly stochastic, with the supernova enriching over 10 G-dwarfs in some clusters, and none at all in others. Typically, only ~25 per cent of clusters contain enriched, unperturbed singletons, and usually only one to two per cluster (from a total of 96 G-dwarfs in each cluster). The initial conditions for star formation do not strongly affect the results, although a higher fraction of supervirial (expanding) clusters would contain enriched G-dwarfs if the supernova occurred earlier than 6.6 Myr. If we sum together simulations with identical initial conditions, then ~1 per cent of all G-dwarfs in our simulations are enriched, unperturbed singletons.

Key words: methods: numerical – stars: formation – planetary systems – open clusters and associations: general.

1 INTRODUCTION
One of the outstanding issues in astrophysics is characterizing the birth environment of the Solar system (e.g. Adams 2011). In particular, understanding whether the Sun is an ‘average’ star in terms of its formation and evolution is important for assessing how likely the formation of a quiescent, habitable Solar system is when placed in the context of other planetary systems.

A strong constraint on the formation of our Solar system appears to be the presence of short-lived radioactive isotopes in meteorites originating from the epoch of planet formation (Lee, Papanastassiou & Wasserburg 1976). The short half-life and abundance of such isotopes (inferred from their stable daughter products) argue for their rapid inclusion in meteorites during the early phases of the Solar system (Looney, Tobin & Fields 2006; Thrane, Bizzarro & Baker 2006).

Short-lived radiogenic isotopes may also be the dominant heat source for forming planetesimals in protoplanetary discs (Urey 1955; MacPherson, Davis & Zinner 1995). This could affect the survival of volatile elements in the inner region of the Solar system and have implications for planet habitability (Nimmo 2002).

Several short-lived isotopes with half-lives ranging from tens of days to several Myr are present in meteorites, but two – 26Al and 60Fe – are very difficult to produce without nucleosynthesis in massive stars (e.g. Goswami 2004). It is possible to produce 26Al through spallation (Lee et al. 1998; Shu et al. 2001) or from evolved asymptotic giant branch stars (Busso, Gallino & Wasserburg 1999, ...)
2003), but the presence of $^{60}$Fe points towards enrichment from a supernova explosion (see e.g. the discussion in Adams 2011). 1

Following the discovery of $^{26}$Al in meteorites, Cameron & Truran (1977) suggested that the Sun could have formed when a supernova explosion triggered the collapse of a star-forming giant molecular cloud (GMC; see also Boss 1995; Cameron et al. 1995; Boss & Vanhala 2000; Boss & Keiser 2012). This scenario requires that the supernova explosion does not destroy the GMC altogether.

Other authors have suggested that whereas $^{60}$Fe may be delivered from a supernova, $^{26}$Al can also be produced in the winds of evolved massive stars (Gounelle & Meynet 2012), and that the isotope enrichment occurs in a sequential star formation process. First, $^{60}$Fe is delivered to the nearby ISM by multiple supernovae from the first generation of star formation. These supernovae then trigger a second generation of star formation in which $^{26}$Al is delivered into the ISM by the wind of a single massive star. The Sun is then born in a third generation of star formation within the shell of contaminated ISM material.

Finally, $^{26}$Al and $^{60}$Fe can be delivered directly to the disc from which the Solar system formed (Chevalier 2000; Ouellette, Desch & Hester 2007). In this scenario, the massive star is assumed to form coevally with the Sun, but it evolves faster and the resultant core-collapse supernova occurs before the protoplanetary disc has begun to coalesce and form large planetesimals. To obtain the correct enrichment levels, Chevalier (2000) and Ouellette et al. (2007) suggest that the Sun’s protoplanetary disc must have been between 0.1 and 0.3 pc from the supernova (at distances less than 0.1 pc, the supernova is likely to strip away too much of the disc, and beyond 0.3 pc the yield of radioactive isotopes is too low; Adams 2011).

If the meteorite enrichment occurs during a single supernova explosion, then a 25 M$_\odot$ star is most likely to deliver the relative isotopic abundances (Wasserburg et al. 2006). At first sight, a 25 M$_\odot$ star in close proximity to the Sun may seem unlikely; most stars form in clusters or associations (Lada & Lada 2003) and there is a relation between the most massive star that can form in a cluster and the mass of the cluster (cf. number of stars) itself (Weidner, Kroupa & Pfalzner 2013). Adams & Laughlin (2001) show that when randomly sampling an initial mass function (IMF) a 25 M$_\odot$ star is likely to form in a cluster with at least $N = 2000 \pm 100$ other stars (the exact number of stars depends on the adopted IMF).

This moderately high expectation value for the number of stars that form in the company of a 25 M$_\odot$ star, coupled with the fact that embedded clusters typically have radii less than several pc (Lada & Lada 2003), suggests that the birth environment of the Solar system could be rather dense and therefore hostile. UV radiation from massive stars, which would evaporate or truncate the protoplanetary disc (Armitage 2000; Scally & Clarke 2001; Adams et al. 2004), and dynamical interactions during close encounters with intermediate- and low-mass stars (Bonnell et al. 2001; Adams et al. 2006; Parker & Quanz 2012) could inhibit planet formation in such an environment.

Several authors have estimated the maximum number of stars in the Sun’s natal cluster that would allow the formation of a 25 M$_\odot$ star, but also not be too hostile for the formation and evolution of the Solar system. For example, Adams & Laughlin (2001), Adams et al. (2006) and Dukes & Krumholz (2012) calculate collisional cross-sections for the Solar system to undergo disruptive interactions with passing stars, and Pfalzner (2013) calculates the likely encounter rates for Sun-like stars in two different types of star-forming region: an extremely dense cluster versus a more diffuse OB association.

In general, these authors find that a cluster with $N = 10^3$–$10^4$ stars would enable the formation of a 25 M$_\odot$ star without dynamical interactions prohibiting the formation of the Solar system – provided that the cluster quickly disperses (Dukes & Krumholz 2012; Pfalzner 2013).

However, it remains unclear whether the evolution of a ‘typical’ cluster which forms a 25 M$_\odot$ star does result in supernova enrichment of G-dwarf stars like the Sun, without those G-dwarfs suffering dynamical interactions which would hinder or disrupt planet formation. Previous work on this topic has assumed that if the cluster contains a 25 M$_\odot$ star, then enrichment is virtually guaranteed, and instead focuses on whether the encounter history of Sun-like stars in the cluster may be the prohibitive factor in deciding whether the Solar system could form and/or survive. Here, we simultaneously combine the two approaches and determine how many G-dwarfs are within 0.1–0.3 pc of the supernova (in order for the disc to have the correct levels of enrichment; Chevalier 2000; Looney et al. 2006; Ouellette et al. 2007) but do not suffer disruptive dynamical interactions during the course of the cluster’s evolution.

In this paper, we use N-body simulations to model the evolution of star clusters that contain exactly one 25 M$_\odot$ star in a cluster with ~2000 other stars and determine the number of G-dwarfs that experience the necessary supernova enrichment, where the 25 M$_\odot$ star is expected to go supernova at ~6.6 Myr (e.g. Hirschi, Meynet & Maeder 2004). Of those G-dwarfs, we also determine their interaction history within the cluster. We model four different initial cluster set-ups to cover a large range of potential star formation scenarios, but keep the stellar population constant so that stochastic differences in the clusters’ evolution can be identified.

The paper is organized as follows: in Section 2 we describe our method of sampling the IMF to obtain a ‘typical’ cluster, in Section 3 we describe the N-body simulations and in Section 4 we describe the results for four different types of cluster initial conditions. We focus on the dynamical histories of enriched G-dwarfs from a representative simulation in Section 5, we provide a discussion in Section 6 and we conclude in Section 7.

2 A ‘TYPICAL’ CLUSTER

There are two distinct methods for populating a (model) star cluster with stars from an IMF: random sampling versus sorted sampling. In the first scenario, the mass of the cloud from which stars form is the only upper limit for stellar masses – for example, in very rare scenarios a 100 M$_\odot$ cluster could (mathematically) produce a 100 M$_\odot$ star (e.g. Elmegreen 2006; Parker & Goodwin 2007). In the second scenario, there is a direct physical dependence between the cluster mass and the most massive star that can form (Weidner & Kroupa 2006; Weidner et al. 2013). Weidner et al. (2013) claim that the latter scenario is supported by the observation that many clusters follow a relation that is consistent with sorted sampling (though see Maschberger & Clarke 2008). Such a relation would not be fundamental if massive stars could be definitively shown to form in (relative) isolation, and recent work by Lamb et al. (2010), Bressert et al. (2012) and Oey et al. (2013) have shown many tens of O-type stars to be apparently isolated.

However, the issue of random versus sorted sampling is still the subject of much debate, with Cerviño et al. (2013) claiming that it is statistically impossible to prove one scenario over the other. The discussion is relevant here because sorted sampling implies

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1 Note that recent work (e.g. Moynier et al. 2011; Tang & Dauphas 2012) has suggested that the abundance of $^{60}$Fe in the early Solar system may not be as high as previously thought, and could be as low as the levels measured in the background interstellar medium (ISM).
that a minimum number of stars (~2000) is required for a cluster to host a 25 M⊙ star. Any G-dwarf enriched by the supernova could then be subject to dynamical interactions in this populous cluster. If a cluster was populated randomly from the IMF, then a 25 M⊙ star could form with very few companions – in this scenario the low probability of this cluster forming could then outweigh the probability of a G-dwarf not suffering perturbing interactions in a more populous cluster.

In this paper, we will not consider the dynamical histories of clusters with ‘unusual’ IMFs from random sampling. Instead, we use the results of Monte Carlo experiments from Parker & Goodwin (2007), who randomly sampled a Kroupa (2002) IMF to examine the distribution in cluster mass of clusters that contain only one massive star (>17.5 M⊙). The median cluster mass from 10⁸ realizations of a cluster where the most massive star is 25 M⊙ corresponds to ~2100 stars, which is also consistent with values expected from the sorted sampling method advocated by Weidner & Kroupa (2006) – compare figs 4 and 5 in Parker & Goodwin (2007).

3 CLUSTER MODELS

We conduct pure N-body simulations of four different dynamical scenarios for cluster evolution, characterized by the initial virial ratio αvir = T/Ω, where T and |Ω| are the total kinetic energy and total potential energy of the stars, respectively. We will first discuss clusters in virial equilibrium (αvir = 0.5) with a smooth radial profile. We will then discuss substructured clusters with three different initial virial states: subvirial (‘cool’ – αvir = 0.3), virial (‘ tepid’ – αvir = 0.5) and supervirial (‘warm’ – αvir = 0.7).

To obtain an idea of the stochasticity in the simulations, we model 20 different realizations of the same cluster. We retain the same stellar population, but set the positions and velocities of the stellar systems with a different random number each time.

3.1 Dynamical evolution

We evolve the clusters for 10 Myr using the KIRA integrator in the STARLAB package (e.g. Portegies Zwart et al. 1999, 2001). This follows the clusters until they have started to dissolve and hence contribute to the Galactic field population. Parker & Quanz (2012) found that at 10 Myr a significant fraction (20–40%) of stars are unbound in similar clusters to those modelled here, and Allison et al. (2010) noted that the more substructured a cluster is, the more likely it is to evaporate on time-scales less than 10 Myr. We do not impose an external Galactic tidal field on the clusters, as this will have only a minimal effect in the first 10 Myr. We implement stellar and binary evolution by using the SEBA code (Portegies Zwart & Verbunt 1996, 2012), also within STARLAB, which updates the evolutionary state of stars more frequently than the timestep of the N-body integrator. The combination of KIRA and SEBA enables us to model the clusters as fully collisional systems with accurate stellar evolution (including stellar mergers and binary evolution).

3.2 Smooth clusters in virial equilibrium

We model smooth clusters in virial equilibrium using a Plummer sphere (Plummer 1911), according to the prescription in Aarseth, Hénon & Wielen (1974). We force the most massive star in the cluster to be at the cluster centre, as mass segregation is observed in several large clusters, and smooth, virialized clusters cannot mass segregate dynamically on short time-scales (Bonnell & Davies 1998). The Plummer spheres have a half-mass radius of 0.4 pc.

3.3 Substructured clusters

We set up substructured clusters using the fractal prescription in Goodwin & Whitworth (2004). This has the advantage that the substructure is described by just one parameter, the fractal dimension D. In three dimensions, a highly substructured cluster has a fractal dimension D = 1.6, and a uniformly spherical cluster has D = 3.0. We set up clusters with a moderate level of substructure, with D = 2.0.

The velocities of the stellar systems (be they single or binary) are correlated according to the substructure; stars that are close have similar velocities, whereas distant stars can have very different velocities (Goodwin & Whitworth 2004). We refer the reader to Goodwin & Whitworth (2004), Allison et al. (2010) and Parker, Goodwin & Allison (2011) for a fuller description of this cluster set-up method. The fractals have a radius of 1 pc.

We then vary the initial virial ratio of the stars and scale the velocities of the individual stars to the desired virial ratio. In one suite of simulations, the clusters are subvirial (αvir = 0.3), which results in cool collapse during the first 1 Myr (Allison et al. 2010). In this set-up, the most massive stars are placed at random in the fractal – they may subsequently mass segregate so that the massive stars sink to the centre of the cluster. Another suite of simulations are initially in virial equilibrium (αvir = 0.5) – the initial substructure is subsequently erased through dynamical interactions, but the cluster is not expected to form a central core which is as dense as that in the cool-collapse clusters. Finally, we run a suite of simulations where the stars are initially supervirial (αvir = 0.7) – to determine whether supernova enrichment of G-dwarfs can occur if the birth cluster is globally unbound.

3.4 Stellar systems

We place the same population of stellar systems in each cluster to establish that any differences in the evolution of the clusters are due to the random differences in system velocity or position, rather than total mass or different binary properties.

The majority of G-type stars in the Galactic field have a binary companion (Duquennoy & Mayor 1991; Raghavan et al. 2010). We include binaries in our simulations for the reason that a Sun-like star that experiences the necessary amount of supernova enrichment may not be a suitable Solar system analogue if it is in a close (<100 au) binary system.

We set the most massive star in the cluster to be 25 M⊙ and then draw the remaining primary masses randomly from a Kroupa (2002) IMF of the form

\[
\frac{dN}{dM} \propto \begin{cases} 
M^{-1.3} & m_0 < M/M_\odot \leq m_1, \\
M^{-2.3} & m_1 < M/M_\odot \leq m_2,
\end{cases}
\]

where \(m_0 = 0.1 M_\odot\), \(m_1 = 0.5 M_\odot\), and \(m_2 = 20 M_\odot\), so that we do not have any other \(>20 M_\odot\) (O-type) stars in the clusters.

3.4.1 Binary systems

We set up stellar systems with the binary fraction and orbital parameters observed in the Galactic field. Note that the field is probably a dynamically evolved population; the primordial binary fraction was likely higher, and the period and eccentricity distributions will also have evolved. In principle, it is possible to ‘reverse engineer’ the initial binary population by comparing the observed binary properties in young clusters with simulated clusters (e.g. Parker et al. 2011; King et al. 2012; Geller, Hurley & Mathieu 2013). However, for the
purposes of this paper, we simply wish to impose a lower limit on
the number of G-dwarfs that reside in binary systems initially and
the field population is a suitable lower limit; we will discuss this
assumption in Section 6.

The field binary fraction decreases as a function of the primary
mass. Primary masses are in the range $0.1 \leq M/M_\odot < 0.47$ for
M-dwarfs, with a binary fraction of 0.42 (Fischer & Marcy 1992).
K-dwarfs have masses in the range $0.47 \leq M/M_\odot < 0.84$ with
a binary fraction of 0.45 (Mayor et al. 1992), and G-dwarfs have
masses in the range $0.84 \leq M/M_\odot < 1.2$ with a binary fraction of
0.57 (Duquennoy & Mayor 1991; Raghavan et al. 2010). All stars
more massive than 1.2 $M_\odot$ are grouped together and assigned a
binary fraction of unity, as massive stars have a much larger binary
fraction than low-mass stars (e.g. Abt, Gomez & Levy 1990; Mason
et al. 1998, 2009; Kouwenhoven et al. 2005, 2007; Pfalzner &
Olczak 2007, and references therein). If a random number exceeds
the binary fraction of the primary mass, a secondary mass is drawn
from a flat mass ratio distribution (Reggiani & Meyer 2011).

The periods of binary systems in the field are observed to have a
log-normal distribution (Duquennoy & Mayor 1991; Raghavan et al.
2010) of the form

$$f_{\log_{10}P} \propto \exp\left\{ \frac{-(\log_{10}P - \log_{10}P_0)^2}{2\sigma_{\log_{10}P}^2} \right\},$$

where $\log_{10}P = 4.8$, $\sigma_{\log_{10}P} = 2.3$ and $P$ is in days.

The eccentricities of binary stars are drawn from a thermal dis-
tribution (Heggie 1975) of the form

$$f_\epsilon(\epsilon) = 2\epsilon.$$ 

Figure 1. Dynamical evolution and enrichment in clusters initially in virial equilibrium with a smooth radial profile. In panel (a) we show the initial cluster morphology, and in panel (b) we show the cluster morphology when the 25 $M_\odot$ star goes supernova (at 6.63 Myr) for a typical simulation [cluster number (i) in Table 1]. The position of the supernova progenitor is shown by the black triangle, and the next nine massive stars (with masses 7–13 $M_\odot$) are shown by the red filled circles. In panel (c), we show the cumulative distributions of G-dwarf distances from the supernova explosion; the 0.1–0.3 pc ‘Goldilocks zone’ for enrichment of our own Solar system is between the two vertical dashed lines. For clarity, we only show the distributions for 10 randomly chosen clusters in Table 1. In panel (d), we show the distributions of $N_{\text{enrich}}$ (the open histogram), $N_{\text{enrich, sing}}$ (the grey histogram) and $N_{\text{enrich, sing, unp}}$ (the black histogram) for all 20 simulations.
In the sample of Duquennoy & Mayor (1991), close binaries (with periods less than 10 d) are almost exclusively on tidally circularised orbits. We account for this by reselecting the eccentricity of a system if it exceeds the following period-dependent value:

\[ e_{\text{id}} = \frac{1}{2} \left[ 0.95 + \tanh(0.6 \log_{10} P - 1.7) \right]. \tag{4} \]

We combine the primary and secondary masses of the binaries with their semimajor axes and eccentricities to determine the relative velocity and radial components of the stars in each system.

We continue this procedure until the cluster has 2100 stars, which corresponds to the median cluster mass from 10^5 realizations of a cluster where the most massive star is 25 M_☉ (Parker & Goodwin 2007). The next nine most massive stars in this cluster range from 7 to 13 M_☉, and the cluster contains a total of 96 G-dwarfs. The single stars and binaries are then placed randomly at a system position in the fractal or Plummer sphere.

4 CLUSTER EVOLUTION

In this section, we consider four different sets of initial conditions for star cluster formation and follow the subsequent dynamical evolution for 10 Myr. For each cluster, we determine the number of G-dwarfs, \( N_{\text{enrich}} \), that are within 0.1–0.3 pc of the supernova and therefore experience the required levels of isotope enrichment observed in Solar system meteorites (Chevalier 2000; Ouellette et al. 2007). Of these \( N_{\text{enrich}} \) G-dwarfs, we then determine how many are either in close (\(<100 \text{ au}\)) binary systems or suffer a close (\(<100 \text{ au}\)) encounter that could affect the outer regions of the Solar system (Adams & Laughlin 2001; Adams et al. 2006; Dukes & Krumholz 2012). We label the number of these enriched ‘singletons’ (Malmberg et al. 2007) \( N_{\text{enrich, sing}} \). Finally, we might expect that a large velocity perturbation could disrupt planet formation (or a young system of planets). We therefore count the number of enriched singletons that do not suffer a velocity kick greater than 1 km s\(^{-1}\) (the typical velocity dispersion in a bound embedded cluster) as being dynamically unperturbed, \( N_{\text{enrich, sing, unp}} \).

In Section 5, we will show the dynamical histories of several enriched G-dwarfs in a representative simulation, but in this section we focus on whether the numbers of enriched G-dwarfs depend on the different adopted initial conditions for star formation.

4.1 Smooth, virial clusters

We show the typical morphology of a smooth Plummer-sphere cluster at 0 Myr (Fig. 1a) and at the supernova time (6.63 Myr – Fig. 1b). The black triangle indicates the position of the supernova progenitor at each time. The cumulative distributions of distances from the supernova for all 96 G-dwarfs for 10 clusters are shown in Fig. 1(c). The 0.1–0.3 pc ‘Goldilocks zone’ for enrichment of our own Solar system is between the two vertical dashed lines.

As one might expect, the smooth Plummer-sphere clusters in virial equilibrium follow very similar evolutionary patterns. They all retain a smooth, centrally concentrated morphology. However, the number of enriched G-dwarfs \( N_{\text{enrich}} \) does vary between clusters, as does the number of enriched, unperturbed singletons \( N_{\text{enrich, sing, unp}} \). In Fig. 1(d), we show the distribution of \( N_{\text{enrich}} \) in all 20 simulations by the open histogram, the distribution of \( N_{\text{enrich, sing}} \) by the grey histogram and the distribution of \( N_{\text{enrich, sing, unp}} \) by the black histogram. Note that the simulations are sorted by \( N_{\text{enrich, sing, unp}} \), \( N_{\text{enrich, sing}} \) and then \( N_{\text{enrich}} \).

Table 1. Data from the simulations in which the cluster is in virial equilibrium with a smooth (Plummer-sphere) morphology. We show the simulation number, total number of enriched G-dwarfs, \( N_{\text{enrich}} \), the number of enriched G-dwarfs that are ‘singletons’ – i.e. they are never in a binary or suffer an interaction with a semimajor axis less than 100 au, \( N_{\text{enrich, sing}} \), and the number of enriched singletons that do not suffer significant velocity perturbations, \( N_{\text{enrich, sing, unp}} \).

| Simulation no. | \( N_{\text{enrich}} \) | \( N_{\text{enrich, sing}} \) | \( N_{\text{enrich, sing, unp}} \) |
|---------------|----------------|----------------|----------------|
| (i)           | 5             | 3              | 3              |
| (ii)          | 13            | 6              | 2              |
| (iii)         | 8             | 2              | 2              |
| (iv)          | 13            | 3              | 2              |
| (v)           | 8             | 3              | 2              |
| (vi)          | 7             | 3              | 2              |
| (vii)         | 4             | 2              | 2              |
| (viii)        | 8             | 5              | 1              |
| (ix)          | 12            | 4              | 1              |
| (x)           | 7             | 4              | 1              |
| (xi)          | 4             | 3              | 1              |
| (xii)         | 8             | 2              | 0              |
| (xiii)        | 3             | 1              | 0              |
| (xiv)         | 2             | 1              | 0              |
| (xv)          | 4             | 0              | 0              |
| (xvi)         | 0             | 0              | 0              |
| (xvii)        | 0             | 0              | 0              |
| (xviii)       | 0             | 0              | 0              |
| (xix)         | 0             | 0              | 0              |
| (xx)          | 0             | 0              | 0              |

\(^{a}\)Supernova progenitor ejected after an interaction with a massive binary.

\(^{b}\)Supernova progenitor ejected after interactions with other massive stars.

\(^{c}No supernova: a 25 M_☉ star merged with a 5 M_☉ star at 5.73 Myr.\)

First, 5/20 clusters do not contain any enriched G-dwarfs. This is mainly due to the supernova progenitor interacting with the other massive stars in the cluster and being ejected; however, in one cluster [number (xx) in Table 1] the 25 M_☉ star merges with a 5 M_☉ star and the product does not explode as a supernova before the end of the simulation.

In the 15 simulations where we do have supernova enrichment, the number of enriched G-dwarfs, \( N_{\text{enrich}} \), varies between 2 and 13 (from a total of 96 G-dwarfs). 14/20 clusters contain between one and six enriched stars that are singletons, and 11/20 clusters contain one, two or three enriched singletons that are unperturbed. We summarize the results in Table 1.

4.2 Substructured, subvirial clusters

We show the typical morphology of a substructured, subvirial cluster at 0 Myr (Fig. 2a) and at the supernova time (6.63 Myr – Fig. 2b). The black triangle indicates the position of the supernova progenitor each time. We see that the initial substructure has been completely erased, and the cluster has now assumed a smooth, centrally concentrated profile with a dense core. The most massive stars have dynamically mass segregated and are at the centre of the cluster, implying that the G-dwarfs that are enriched by the supernova must pass through the centre of the cluster at least once.

Substructured clusters evolve very stochastically, especially those undergoing cool collapse (Allison et al. 2010; Parker & Goodwin 2012). The violent relaxation process these clusters undergo can

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lead to the ejection of massive stars, often after they have become the member of an unstable Trapezium-like system (Allison & Goodwin 2011).

The cumulative distributions of distances from the supernova for all 96 G-dwarfs for 10 clusters are shown in Fig. 2(c). The 0.1–0.3 pc ‘Goldilocks zone’ for enrichment of our own Solar system is between the two vertical dashed lines.

In Fig. 2(d), we show the distribution of $N_{\text{enrich}}$ in all 20 simulations by the open histogram, the distribution of $N_{\text{enrich, sing}}$ by the grey histogram and the distribution of $N_{\text{enrich, sing, unp}}$ by the black histogram.

8/20 clusters do not have any enriched G-dwarfs, often due to the supernova progenitor interacting with the other massive stars in short-lived and unstable Trapezium-like systems, resulting in the ejection of the progenitor. Examples of this are shown in Fig. 2(c) by the green and blue lines on the far right of the panel, which are the cumulative distributions of G-dwarf distances from simulations (xvi) and (xvii) in Table 2.

In the 12 simulations where we do have supernova enrichment, the number of enriched G-dwarfs, $N_{\text{enrich}}$, varies between 3 and 10 (from a total of 96 G-dwarfs). 9/20 clusters contain between one and seven enriched stars that are singletons, and 6/20 clusters contain one, two or three enriched singletons that are unperturbed, $N_{\text{enrich, sing, unp}}$. We summarize the results in Table 2.

### 4.3 Substructured, virial clusters

We show the typical morphology of an initially substructured, virialized cluster at 0 Myr (Fig. 3a) and at the supernova time (6.65 Myr – Fig. 3b). The black triangle indicates the position of the supernova progenitor each time. The majority of these clusters lose substructure within the first few Myr of evolution, although one cluster [number (xx) in Table 3] retains substructure in the sense that it forms a ‘binary cluster’ – a cluster with two distinct groups of stars.

Substructured, virialized clusters are also dense enough to eject the supernova progenitor – again, usually from unstable
Substructured, supervirial clusters tend to retain some substructure (Parker & Meyer 2012). In around half of these simulations, a binary cluster forms (Fig. 4b) – with the most massive star (i.e. the supernova progenitor) likely to be in one of the binary ‘nodes’. Even though the global motion causes the cluster to expand, these nodes are dense enough for enrichment to occur in around half of the clusters. The remainder of these supervirial fractals expand to form association-like structures, which are too diffuse for the required G-dwarf enrichment (the clusters with $N_{\text{enrich}} = 0$ in Table 4).

The cumulative distributions of distances from the supernova for all 96 G-dwarfs for 10 clusters are shown in Fig. 4(c). The 0.1–0.3 pc ‘Goldilocks zone’ for enrichment of our own Solar system is between the two vertical dashed lines. Binary clusters are betrayed in this plot by the step-like cumulative distributions in some simulations.

In Fig. 4(d), we show the distribution of $N_{\text{enrich}}$ in all 20 simulations by the open histogram, the distribution of $N_{\text{enrich, sing}}$ by the grey histogram and the distribution of $N_{\text{enrich, sing, unp}}$ by the black histogram.

9/20 clusters do not have any enriched G-dwarfs. In the 11 simulations where we do have supernova enrichment, the number of enriched G-dwarfs, $N_{\text{enrich}}$, varies between 1 and 14 (from a total of 96 G-dwarfs). 6/20 clusters contain between one and three enriched stars that are singletons, and 5/20 clusters contain one or two enriched singletons that are unperturbed. We summarize the results in Table 4.

### 5 Dynamical Histories

In the previous section, we showed the number of G-dwarf stars that were enriched at a distance between 0.1 and 0.3 pc from the supernova ($N_{\text{enrich}}$) as a function of initial cluster conditions. Of those $N_{\text{enrich}}$, we determined the number $N_{\text{enrich, sing}}$ that were singletons, meaning that they were never in a close binary system, nor did they suffer a sub-100 au encounter. Either scenario would most likely preclude the formation and stable evolution of our Solar system. Finally, we applied a stricter criterion that an enriched singleton suffering a strong velocity perturbation (i.e. in excess of the typical velocity dispersion in a cluster) could also be prohibited from forming a stable Solar system. The number of systems that are enriched singletons that do not suffer such perturbations is $N_{\text{enrich, sing, unp}}$.

Here, we focus on the dynamical histories of three enriched G-dwarfs in a representative simulation where the cluster is initially substructured and subvirial [number (vi) in Table 2]. Because the substructure is erased on short time-scales ($< 2$ Myr) in subvirial and virial clusters, the subsequent dynamical evolution of the cluster is similar, irrespective of the assumed initial morphology. The only exception is a supervirial (unbound) cluster, which expands and so does not have a well-defined ‘centre’. However, when supernova enrichment does occur in supervirial clusters, the parameters we concentrate on here (nearest-neighbour distance to the enriched G-dwarf and velocity perturbations) are similar for all initial morphologies and virial states.

In the chosen simulation, $N_{\text{enrich}} = 3$ G-dwarfs were enriched by the supernova. In Fig. 5(a), we show the distance to the nearest neighbour of each enriched G-dwarf as a function of time. One of the G-dwarfs is in a close (~10 au) binary (the black line), and therefore is not a ‘singleton’ and cannot be an analogue of our own Solar system. The remaining two enriched G-dwarfs have occasional encounters that are of the order of 500 au. Encounters of this magnitude have been suggested as potential mechanisms to create the high eccentricities of some Edgeworth–Kuiper belt

### Table 2. Data from the simulations in which the cluster is substructured and subvirial. We show the simulation number, the total number of enriched G-dwarfs, $N_{\text{enrich}}$, the number of enriched G-dwarfs that are ‘singletons’ – i.e. they are never in a binary or suffer an interaction with a semimajor axis less than 100 au, $N_{\text{enrich, sing}}$, and the number of enriched singletons that do not suffer significant velocity perturbations, $N_{\text{enrich, sing, unp}}$.

| Simulation no. | $N_{\text{enrich}}$ | $N_{\text{enrich, sing}}$ | $N_{\text{enrich, sing, unp}}$ |
|---------------|---------------------|---------------------------|-----------------------------|
| (i)           | 7                   | 4                         | 3                           |
| (ii)          | 8                   | 2                         | 2                           |
| (iii)         | 8                   | 7                         | 1                           |
| (iv)          | 10                  | 3                         | 1                           |
| (v)           | 8                   | 3                         | 1                           |
| (vi)          | 3                   | 2                         | 1                           |
| (vii)         | 9                   | 2                         | 0                           |
| (viii)        | 6                   | 1                         | 0                           |
| (ix)          | 5                   | 1                         | 0                           |
| (x)           | 10                  | 0                         | 0                           |
| (xi)          | 4                   | 0                         | 0                           |
| (xii)         | 4                   | 0                         | 0                           |
| (xiii)        | 4                   | 0                         | 0                           |
| (xiv)         | 0                   | 0                         | 0                           |
| (xv)          | 0                   | 0                         | 0                           |
| (xvi)         | 0                   | 0                         | 0                           |
| (xvii)        | 0                   | 0                         | 0                           |
| (xviii)       | 0                   | 0                         | 0                           |
| (xix)         | 0                   | 0                         | 0                           |
| (xx)          | 0                   | 0                         | 0                           |

*a Supernova progenitor ejected after an interaction with a massive binary.
*b Supernova progenitor ejected after interactions with other massive stars.
*c Supernova progenitor ejected from an unstable Trapezium-like system.
*d No G-dwarfs between 0.1 and 0.3 pc from the supernova due to the cluster’s rapid expansion.

Trapezium-like systems. The binary cluster (xx) is not dense enough to have any G-dwarfs in the 0.1–0.3 pc enrichment range, although as we will see in the case of supervirial clusters, the formation of a binary cluster does not preclude enrichment.

The cumulative distributions of distances from the supernova for all 96 G-dwarfs for 10 clusters are shown in Fig. 3(c). The 0.1–0.3 pc ‘Goldilocks zone’ for enrichment of our own Solar system is between the two vertical dashed lines.

In Fig. 3(d), we show the distribution of $N_{\text{enrich}}$ in all 20 simulations by the open histogram, the distribution of $N_{\text{enrich, sing}}$ by the grey histogram and the distribution of $N_{\text{enrich, sing, unp}}$ by the black histogram.

7/20 clusters do not have any enriched G-dwarfs. In the 13 simulations where we do have supernova enrichment, the number of enriched G-dwarfs, $N_{\text{enrich}}$, varies between 1 and 13 (from a total of 96 G-dwarfs). 11/20 clusters contain between one and four enriched stars that are singletons, and 5/20 clusters contain one, three or four enriched singletons that are unperturbed. We summarize the results in Table 3.

### 4.4 Substructured, supervirial clusters

We show the typical morphology of an initially substructured, supervirial cluster at 0 Myr (Fig. 4a) and at the supernova time (6.64 Myr – Fig. 4b). The black triangle indicates the position of the supernova progenitor each time.
Figure 3. Dynamical evolution and enrichment in initially substructured, virialized (tepid) clusters. In panel (a) we show the initial cluster morphology, and in panel (b) we show the cluster morphology when the 25 $M_\odot$ star goes supernova (at 6.65 Myr) for a typical simulation [cluster (i) in Table 3]. The position of the supernova progenitor is shown by the black triangle, and the next nine massive stars (with masses 7–13 $M_\odot$) are shown by the red filled circles. In panel (c), we show the cumulative distributions of G-dwarf distances from the supernova explosion; the 0.1–0.3 pc ‘Goldilocks zone’ for enrichment of our own Solar system is between the two vertical dashed lines. For clarity, we only show the distributions for 10 randomly chosen clusters in Table 3. In panel (d), we show the distributions of $N_{\text{enrich}}$ (the open histogram), $N_{\text{enrich, sing}}$ (the grey histogram) and $N_{\text{enrich, sing, unp}}$ (the black histogram) for all 20 simulations.

In Fig. 5(b), we show the distance from the cluster centre for each of the $N_{\text{enrich, sing}} = 2$ singletons in the simulation. Due to dynamical mass segregation, the supernova progenitor has sunk to the cluster centre before the explosion, and both G-dwarfs are required to be on clustercentric orbits to enable enrichment. This has two implications for our two enriched singletons. First, they must pass through the cluster centre at least once – during this time their discs could be subject to photoevaporation (e.g. Armitage 2000; Scally & Clarke 2001; Adams et al. 2004) from other massive stars, which are also likely to reside in the cluster centre. Inspection of Fig. 5(b) shows that one of our singletons, shown by the red line, passes through the inner 0.5 pc of the cluster centre much more often than the other (shown by the green line). Secondly, at the time of the supernova (shown by the dotted vertical line in all panels), the singletons just happen to be passing through the cluster centre at that instant – they are ‘in the right place at the right time’.

Finally, we show the change in velocity magnitude for the enriched singletons in Fig. 5(c). One of these singletons experiences velocity kicks in excess of 1 km s$^{-1}$ (the red line), which we suggest could disrupt planet formation and/or evolution. We note that this enriched singleton also passes through the cluster centre more often, and therefore it is not surprising that it has a more hostile dynamical history than the other enriched singleton in this cluster.

6 DISCUSSION

In Sections 4 and 5, we have presented the results of $N$-body simulations of star cluster evolution in which we have investigated the numbers of solar-type (G-dwarf) stars that could be enriched in short-lived isotopes by ejecta from the supernova of a 25 $M_\odot$ star.
In this scenario, a supernova enriches the Sun’s protoplanetary disc with the levels of $^{26}$Al and $^{56}$Fe found in meteorites from the epoch of planet formation (Lee et al. 1976; Adams 2011). In order to examine the enrichment levels required without stripping too much of the disc away, the G-dwarf(s) must be within 0.1–0.3 pc of the supernova explosion (Chevalier 2000; Ouellette et al. 2007).

We have varied the initial conditions of the star cluster in an attempt to cover as much parameter space as possible for the initial conditions of star-forming regions that are likely to produce at least one 25 M$_\odot$ star. In our first simulation, we adopt a smooth, virialized Plummer (1911) morphology; this model is unlikely to be representative of the initial conditions of star-forming regions, which exhibit a high degree of substructure (e.g. Cartwright & Whitworth 2004; Sánchez & Alfaro 2009). However, we expect the evolution of Plummer spheres to be less stochastic than fractal clusters (Parker & Goodwin 2012), so these simulations provide a useful benchmark comparison to the fractal simulations.

In the remaining three suites of simulations, we have created clusters with primordial substructure, and also varied the initial virial ratio. Observations of stars in star-forming regions have shown them to have subvirial (cool) velocities (e.g. Peretto, André & Belloche 2006; Fúrész et al. 2008), which in tandem with primordial substructure facilitates a violent relaxation process resulting in a dense spherical cluster (Allison et al. 2010). Such initial conditions have been successful in explaining the Orion nebula cluster, but do not lead to the formation of unbound associations. Indeed, massive unbound associations (e.g. Sco–Cen, Carina) have been suggested as the more likely birthplace of the Solar system, and such regions are observed to contain short-lived radioactive isotopes from nucleosynthesis (e.g. Diehl et al. 2010; Voss et al. 2012). For this reason, we also ran simulations of substructured clusters with virialized (tepid) and supervirial (warm) velocities to investigate whether an unbound association could be a likely birthplace of the Sun (see also Pfalzner 2013).

Somewhat surprisingly, the assumed initial virial ratio does not greatly affect the results. In the initially substructured models, 6/20 cool clusters and 5/20 tepid clusters contain enriched, unperturbed singleton G-dwarfs. The warm, substructured clusters also host a low number of potential Solar system analogues (6/20 clusters contain enriched unperturbed singletons). However, in this case the low densities achieved by these expanding associations are the cause of the low number, rather than hostile dynamical interactions. As an example, supervirial cluster number (xviii) in Table 4 contains 0 enriched, unperturbed singletons. However, if we assume that the supernova exploded at 4 Myr instead of 6.64 Myr, then the cluster contains six unperturbed singletons (from a total of 12 enriched G-dwarfs).

Adding substructure to the clusters does appear to influence the results. In the Plummer models, we find that 15/20 clusters contain enriched G-dwarfs, but applying our constraints that the star must be a singleton and not suffer a perturbing velocity kick we find that 11/20 clusters contain several enriched, unperturbed singleton G-dwarfs. This is roughly a factor of 2 higher than the number of substructured clusters that contain enriched, unperturbed singletons, and is likely due to the fact that Plummer spheres are relaxed potentials, whereas the fractals take more than 1 Myr to relax (Allison et al. 2010) and are therefore less quiescent environments.

One interesting aspect of our results is that the numbers of enriched, unperturbed singletons in the clusters are rather uniform (albeit subject to low-number statistics) compared to the distribution of the number of enriched G-dwarfs. Taking two substructured, tepid clusters as an example, cluster number (i) in Table 3 contains 5 enriched G-dwarfs, 4 of which are unperturbed singletons, whereas cluster (ii) contains 15 enriched G-dwarfs, but only 3 unperturbed singletons. This highlights two processes within the numerical simulations; first, the evolution of the clusters is highly stochastic (even the Plummer spheres contain a wide spread in $N_{\text{enrich}}$) and secondly, large numbers of enriched stars equate to the supernova occurring in a particularly dense region. The higher chances of one of the 96 G-dwarfs experiencing enrichment in a dense cluster must be offset by the fact that the G-dwarfs will likely suffer more dynamical interactions and close encounters.

We caution that the number of enriched, unperturbed singletons from our simulations may be overestimated because we have assumed a field-like primordial binary fraction for G-dwarfs in the clusters. Current estimates suggest that the binary fraction in the field is ~46 per cent (Raghavan et al. 2010) which may be significantly lower than the primordial binary fraction (likely to be between 75 and 100 per cent; e.g. Kaczmarek, Olszak & Pfalzner 2011; Parker et al. 2011; King et al. 2012), due to dynamical processing. If we were to increase the binary fraction of the G-dwarfs, we would expect fewer enriched G-dwarfs to be ‘singletons’ throughout the evolution of the cluster.

In addition to the supernova time, the other constraint for enrichment is that the supernova explodes between 0.1 and 0.3 pc from the G-dwarf (a balance between stripping away too much of the protosolar nebula and injecting enough radioactive isotopes into

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### Table 3

Data from the simulations in which the cluster is substructured and in virial equilibrium. We show the simulation number, the total number of enriched G-dwarfs, $N_{\text{enrich}}$, the number of enriched G-dwarfs that are ‘singletons’ – i.e. they are never in a binary or suffer an interaction with a semimajor axis less than 100 au, $N_{\text{enrich, sing}}$, and the number of enriched singletons that do not suffer significant velocity perturbations, $N_{\text{enrich, sing, unp}}$.

| Simulation no. | $N_{\text{enrich}}$ | $N_{\text{enrich, sing}}$ | $N_{\text{enrich, sing, unp}}$ |
|---------------|----------------------|-----------------------------|-------------------------------|
| (i)           | 5                    | 4                           | 4                             |
| (ii)          | 15                   | 3                           | 3                             |
| (iii)         | 13                   | 3                           | 1                             |
| (iv)          | 6                    | 3                           | 1                             |
| (v)           | 5                    | 3                           | 1                             |
| (vi)          | 8                    | 2                           | 0                             |
| (vii)         | 8                    | 2                           | 0                             |
| (viii)        | 5                    | 2                           | 0                             |
| (ix)          | 3                    | 2                           | 0                             |
| (x)           | 3                    | 2                           | 0                             |
| (xi)          | 1                    | 1                           | 0                             |
| (xii)         | 2                    | 0                           | 0                             |
| (xiii)        | 1                    | 0                           | 0                             |
| (xiv)         | 0                    | 0                           | 0                             |
| (xv)          | 0                    | 0                           | 0                             |
| (xvi)         | 0                    | 0                           | 0                             |
| (xvii)        | 0                    | 0                           | 0                             |
| (xviii)       | 0                    | 0                           | 0                             |
| (xix)         | 0                    | 0                           | 0                             |
| (xx)          | 0                    | 0                           | 0                             |

$^a$Supernova progenitor ejected after an interaction with a massive binary.

$^b$Supernova progenitor ejected after interactions with other massive stars.

$^c$Supernova progenitor ejected from an unstable Trapezium-like system.

$^d$No G-dwarfs between 0.1 and 0.3 pc from the supernova due to fractal evolving into an extended binary cluster.

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In this scenario, a supernova enriches the Sun’s protoplanetary disc with the levels of $^{26}$Al and $^{56}$Fe found in meteorites from the epoch of planet formation (Lee et al. 1976; Adams 2011). In order to examine the enrichment levels required without stripping too much of the disc away, the G-dwarf(s) must be within 0.1–0.3 pc of the supernova explosion (Chevalier 2000; Ouellette et al. 2007).
Supernova enrichment of G-dwarfs

Figure 4. Dynamical evolution and enrichment for initially substructured, supervirial (warm) clusters. In panel (a) we show the initial cluster morphology, and in panel (b) we show the cluster morphology when the 25 $M_\odot$ star goes supernova (at 6.64 Myr) for a typical simulation [cluster (i) in Table 4]. The position of the supernova progenitor is shown by the black triangle, and the next nine massive stars (with masses 7–13 $M_\odot$) are shown by the red filled circles. In panel (c), we show the cumulative distributions of G-dwarf distances from the supernova explosion; the 0.1–0.3 pc ‘Goldilocks zone’ for enrichment of our own Solar system is between the two vertical dashed lines. For clarity, we only show the distributions for 10 randomly chosen clusters in Table 4. In panel (d), we show the distributions of $N_{\text{enrich}}$ (the open histogram), $N_{\text{enrich, sing}}$ (the grey histogram) and $N_{\text{enrich, sing, unp}}$ (the black histogram) for all 20 simulations.

the disc). Panel (c) in Figs 1–4 indicates that a relaxing of this upper bound would imply enrichment of more G-dwarfs; however, the boundary at 0.3 pc already assumes highly efficient injection (Ouellette et al. 2007; Adams 2011) and it is unlikely that this is underestimated.

Our simulations have shown that – whilst it is possible to have multiple enriched, unperturbed singletons in a cluster – 50–75 per cent of the clusters we model do not contain any. Furthermore, the late-stage injection of $^{26}$Al and $^{60}$Fe, which occurs at 6.6 Myr for a supernova with progenitor mass 25 $M_\odot$, has been cited by Gounelle & Meibom (2008) and Gounelle & Meynet (2012) as being too late in the disc evolution to be homogeneously included in the meteorites. This could in principle be alleviated if the supernova progenitor formed first, and the lower mass stars formed several Myr later, although this would require firm evidence of age spreads in star-forming regions. Evidence for and against such age spreads is currently the subject of much debate (e.g. Jeffries et al. 2011; Reggiani et al. 2011). Recently, however, Bell et al. (2013) suggested that the ages of star-forming regions and open clusters may be underestimated by a factor of 2; if this is the case, then protoplanetary discs are longer lived and the arguments against late-stage injection become weaker.

We are then left with the straightforward question: is late-stage enrichment too uncommon to be a feasible delivery mechanism for the $^{26}$Al and $^{60}$Fe levels in the early Solar system? Models of Solar system formation triggered by a supernova naturally account for the $^{26}$Al (Cameron & Truran 1977; Boss 1995; Gritschneder et al. 2012; Vasileiadis, Nordlund & Bizzarro 2013), but require that $^{60}$Fe abundances in the early Solar system be similar to the background ISM levels (as recently suggested by Moynier et al. 2011; Tang & Dauphas 2012). Indeed, Gounelle et al. (2009) and Gounelle & Meynet (2012) recently proposed a three-stage star formation scenario where the supernovae of several stars produce the $^{60}$Fe, and then trigger the formation of a massive star which produces...
Table 4. Data from the simulations in which the cluster is substructured and supervirial. We show the simulation number, the total number of enriched G-dwarfs, \( N_{\text{enrich}} \), the number of enriched G-dwarfs that are ‘singletons’ – i.e. they are never in a binary or suffer an interaction with a semimajor axis less than 100 au, \( N_{\text{enrich, sing}} \), and the number of enriched singletons that do not suffer significant velocity perturbations, \( N_{\text{enrich, sing, unp}} \).

| Simulation no. | \( N_{\text{enrich}} \) | \( N_{\text{enrich, sing}} \) | \( N_{\text{enrich, sing, unp}} \) |
|---------------|----------------|----------------|----------------|
| (i)           | 4              | 3              | 2              |
| (ii)          | 14             | 1              | 1              |
| (iii)         | 6              | 1              | 1              |
| (iv)          | 3              | 1              | 1              |
| (v)           | 1              | 1              | 1              |
| (vi)          | 2              | 1              | 0              |
| (vii)         | 5              | 0              | 0              |
| (viii)        | 3              | 0              | 0              |
| (ix)          | 2              | 0              | 0              |
| (x)           | 2              | 0              | 0              |
| (xi)          | 1              | 0              | 0              |
| (xii)         | 0              | 0              | 0              |
| (xiii)        | 0              | 0              | 0              |
| (xiv)         | 0              | 0              | 0              |
| (xv)          | 0              | 0              | 0              |
| (xvi)         | 0              | 0              | 0              |
| (xvii)        | 0              | 0              | 0              |
| (xviii)       | 0              | 0              | 0              |
| (xix)         | 0              | 0              | 0              |
| (xx)          | 0              | 0              | 0              |

\( ^* \)No G-dwarfs between 0.1 and 0.3 pc from the supernova due to fractal evolving into a diffuse association.

Evidence of short-lived isotopes in meteorites suggests that the Sun was in close proximity to a 25 \( M_\odot \) star which went supernova at the epoch of planet formation in the Solar system. If these isotopes are delivered to the Sun’s protoplanetary disc, the supernova must have occurred at a distance between 0.1 and 0.3 pc of the Sun. We have conducted \( N \)-body simulations of the dynamical evolution of star clusters with \( N = 2100 \) members, which would be expected to form at least one 25 \( M_\odot \) star under the assumption of a normal IMF. We have determined the number of G-dwarfs that experience the necessary levels of enrichment, and then determined their dynamical histories to ascertain whether they could potentially be Solar system analogues. Our conclusions are the following.

(i) Typically, between 50 and 75 per cent of clusters contain supernova-enriched G-dwarfs at a distance of between 0.1 and 0.3 pc from the supernova. The number of enriched G-dwarfs is in the range of several to over 10 (from a total of 96).
(ii) If we consider only ‘singletons’ – G-dwarfs that are never in close binaries or suffer disruptive encounters – then only ~25 per cent of clusters contain G-dwarfs that are enriched, unperturbed singletons. Usually these clusters contain only one or two such objects.

(iii) The assumed initial conditions for star formation have little impact on the results; there is little difference in the numbers of enriched, unperturbed singletons between substructured clusters which are subvirial (cool collapse), virial (trepid and static) or super-virial (warm and expanding). The only caveat is that if the supernova were to explode earlier, the expanding supervirial clusters would have a higher occurrence of enriched, unperturbed singletons.

(iv) Summing together all the G-dwarfs from each suite of simulations, the global fraction of G-dwarfs that are enriched, unperturbed singletons is of the order of 0.5–1 per cent.

(v) The cluster evolution and numbers of enriched stars are highly stochastic; statistically identical clusters can enrich over 10 G-dwarfs, or only several, or none at all – differences are due to the inherently chaotic nature of star cluster evolution.

At first sight, the N-body models suggest that supernova enrichment of unperturbed singleton G-dwarfs like our Sun is a rare occurrence. However, it does occur in a significant fraction of clusters, and sometimes to more than one G-dwarf in the same cluster. Future investigation of the assumed cluster parameters (IMF, morphology, density, virial state), and the time of the supernova explosion, would be beneficial to investigate whether the probability of disc enrichment can be raised by changing one or more of these parameters.

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