

^{26}Al and the Formation of the Solar System from a Molecular Cloud Contaminated by Wolf-Rayet Winds

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ABSTRACT

In agreement with previous work, we show that the presence of the short-lived radionuclide ^{26}Al in the early Solar System was unlikely ($< 2\% \text{ } a \text{ } priori$ probability) to be the result of direct introduction of supernova ejecta into the gaseous disk during the Class II stage of protosolar evolution. We also show that Bondi-Hoyle accretion of any contaminated residual gas from the Sun's natal star cluster contributed negligible ^{26}Al to the primordial Solar System. Our calculations are consistent with the absence of the oxygen isotopic signature expected with any late introduction of supernova ejecta into the protoplanetary disk. Instead, the presence of ^{26}Al in the oldest Solar System solids (calcium-aluminum-rich inclusions or CAIs) and its apparent uniform distribution with the inferred canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio of $(4.5 - 5) \times 10^{-5}$ support the inheritance of ^{26}Al from the Sun's parent giant molecular cloud. We propose that this radionuclide originated in a prior generation of massive stars that formed in the same molecular cloud and contaminated that cloud by Wolf-Rayet winds. We calculated the Galactic distribution of $^{26}\text{Al}/^{27}\text{Al}$ ratios that arise from such contamination using the established embedded cluster mass and stellar initial mass functions, published nucleosynthetic yields from the winds of massive stars, and by assuming rapid and uniform mixing into the cloud. Although our model predicts that the majority of stellar systems contain no ^{26}Al from massive stars, and that the $a \text{ } priori$

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probability that the $^{26}\text{Al}/^{27}\text{Al}$ ratio will reach or exceed the canonical Solar System value is only $\sim 6\%$, the maximum in the distribution of *non-zero* values is close to the canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio. We find that the Sun most likely formed 4–5 million years (Myr) after the massive stars that were the source of ^{26}Al . Furthermore, our model can explain the initial Solar System abundance of a second, co-occurring short-lived radionuclide, ^{41}Ca , if $\sim 5 \times 10^5$ yr elapsed between ejection of the radionuclides and the formation of CAIs. The presence of a third radionuclide, ^{60}Fe , can be quantitatively explained if (a) the Sun formed immediately after the first supernovae from the earlier generation of stars; (b) only 5% of supernova ejecta was incorporated into the molecular cloud, or (c) the radionuclide originated in an even earlier generation of stars whose contributions to other radionuclides with a shorter half-life had completely decayed.

Subject headings: planetary systems: protoplanetary disks — planetary systems: formation

1. Introduction

1.1. Short-lived radionuclides in the early Solar System

Primitive meteoritic materials contain compelling evidence for the short-lived radionuclides (SLRs) ^{10}Be , ^{26}Al , ^{36}Cl , ^{41}Ca , ^{53}Mn , ^{60}Fe , ^{107}Pd , and ^{182}Hf in the early Solar System (Goswami et al. 2005). These radionuclides have a half-life $\tau_{1/2} < 10$ Myr and are potential high-resolution chronometers of events during the epoch of planet formation (Kita et al. 2005; Krot et al. 2008a), but only if they were introduced at discrete times and were uniformly distributed in the Solar System. The potential sources of these radionuclides inform us about the young Sun’s stellar neighborhood (Hester et al. 2004), or its magnetic interaction with an accretion disk (Shu et al. 1997). The decay of one short-lived radionuclide, ^{26}Al , might have been the principle heat source in planetesimals and responsible for the differentiation of the parent bodies of magmatic iron meteorites in the first 1–2 Myr of the Solar System (Greenwood et al. 2005; Scherstén et al. 2006; Markowski et al. 2006).

The origin of SLRs is controversial. The half-life of each is much shorter than the ~ 100 Myr mixing time of the interstellar medium (de Avillez & Mac Low 2002) and the excess abundances of at least five radionuclides (^{10}Be , ^{36}Cl , ^{26}Al , ^{41}Ca , and ^{60}Fe) require one or more “local” sources in addition to the average Galactic background (Jacobsen 2005). Two principle scenarios emerged soon after the first reports of fossil SLRs in meteorites: (*i*) an origin in one or more neighboring massive stars, either Type II supernova (SN) progenitors (Cameron & Truran 1977) or Wolf-Rayet

(WR) stars (Arnould & Prantzos 1986); and (*ii*) production by irradiation of gas or dust with energetic particles from the active young Sun (Heymann & Dziczkaniec 1976). An alternative scenario invoking an origin in a nearby intermediate-mass asymptotic giant branch star (Wasserburg et al. 1994) is generally discounted because of the very low probability of such an encounter (Kastner & Myers 1994). Each of the two schools of thought has developed elaborate models (Lee et al. 1998; Gounelle et al. 2006; Ouellette et al. 2007) but neither has produced a comprehensive explanation of the origin, abundance, and distribution of all the SLRs (Goswami et al. 2005; Gounelle et al. 2006; Duprat & Tatischeff 2007).

The origins of three SLRs seem unambiguous: (*i*) ^{10}Be ($\tau_{1/2} \sim 1.5$ Myr) inferred from excess ^{10}B (McKeegan et al. 2000) could have been produced by energetic particle irradiation but not by stellar nucleosynthesis. Although magnetic trapping of Galactic cosmic rays in the protosolar molecular cloud has been advanced as an alternative explanation (Desch et al. 2004), it is inconsistent with variations in the inferred initial $^{10}\text{Be}/^{9}\text{Be}$ ratio (McKeegan et al. 2000; Sugiura et al. 2001; Marhas et al. 2002; MacPherson et al. 2003). (*ii*) Excess ^{36}S correlated with the ratio $^{35}\text{Cl}/^{34}\text{S}$ and attributable to the decay of ^{36}Cl ($\tau_{1/2} \sim 0.3$ Myr) was reported in sodalite, an alteration phase that replaced anorthite in CAIs and chondrules from CV chondrites (Lin et al. 2005; Hsu et al. 2006). The inferred $^{36}\text{Cl}/^{35}\text{Cl}$ ratio at the time of sodalite formation is 5×10^{-6} . If the sodalite formed late (> 1.5 Myr after CAI crystallization, based on absence of ^{26}Al), the initial $^{36}\text{Cl}/^{35}\text{Cl}$ ratio was $> 1.6 \times 10^{-4}$. This is inconsistent with a massive stellar source and requires a late episode

of irradiation. (iii) ^{60}Ni excess correlated with the $^{56}\text{Fe}/^{58}\text{Ni}$ ratio is evidence for live ^{60}Fe , a radionuclide that cannot be produced by irradiation and must have originated in one or more massive stars (Tachibana & Huss 2003). High-precision nickel isotope measurements in several groups of magmatic iron meteorites indicate that ^{60}Fe was uniformly distributed in the solar nebula (Dauphas et al. 2008) but its initial abundance, $(^{60}\text{Fe}/^{56}\text{Fe})_0 \sim (0.5 - 1) \times 10^{-6}$, is uncertain (Tachibana et al. 2006; Bizzarro et al. 2007; Quitté et al. 2007; Guan et al. 2007). The lower end of the range of estimates is consistent with the expected abundance in star-forming regions if star formation rates were approximately twice as high at the epoch of Solar System formation (Williams 2008; Gounelle & Meibom 2008a) and/or the half-life of ^{60}Fe is actually longer than the published value ($\tau_{1/2} \approx 1.5$ Myr).

1.2. The origin of ^{26}Al

Ironically, the origin of ^{26}Al ($\tau_{1/2} \sim 0.73$ Myr), the first SLR to be discovered (Lee et al. 1976) and the one best studied, remains an enigma. A significant contribution by irradiation is disputed on the grounds that (i) production models adjusted to achieve the required $^{26}\text{Al}/^{27}\text{Al}$ ratio over-predict the observed initial abundance of ^{41}Ca ($\tau_{1/2} \sim 0.1$ Myr) whose co-occurrence indicates a common origin (Sahijpal & Goswami 1998; Goswami et al. 2003; Marhas & Goswami 2004). Finally, the canonical value [$(4.5 - 5) \times 10^{-5}$] of the initial $^{26}\text{Al}/^{27}\text{Al}$ ratio in the majority of CAIs from primitive chondrites (MacPherson et al. 1995; Jacobsen et al. 2008; Makide et al. 2008), the consistent chronology of CAI and chondrule formation between ^{207}Pb - ^{206}Pb and ^{26}Al - ^{26}Mg systematics (Amelin et al. 2002; Halliday & Kleine 2006; Connelly et al. 2008), and the apparently uniform Mg-isotope compositions of bulk chondrites, Mars, Moon and the Earth (Thrane et al. 2006) are evidence for a uniform distribution thought inconsistent with a central (solar) irradiation source.

Although these observations favor an origin

of ^{26}Al in massive stars, the mechanism and timing of its delivery to the early Solar System remains unclear. Two models have been proposed: instability-induced mixing of gaseous SN ejecta during the molecular cloud core phase (Cameron & Truran 1977), and injection of SLR-bearing dust grains into the later protoplanetary disk (Ouellette et al. 2005). The relatively small cross-section of the solar nebula dictated that the progenitor was within ~ 1 pc of the Solar System (Looney et al. 2006). Such a circumstance is possible only in the dense environment of a large stellar cluster (Hester et al. 2004). Incorporation of hot, low-density gas from SN ejecta into the denser, cooler disk gas is inefficient (Vanhala & Boss 2002; Ouellette et al. 2007; Boss 2008). Instead, Ouellette et al. (2005) proposed that several SLRs, including ^{26}Al , were delivered to the early Solar System as grains that condensed from SN ejecta and vaporized upon entering the relatively high-density gas in the disk (Ouellette et al. 2007). Disks around low-mass cluster stars persist for up to 6 Myr (Haisch et al. 2005; Jayawardhana et al. 2006), longer than the main sequence lifetime of the most massive SN progenitors (Schaller et al. 1992).

However, any explanation for Solar System ^{26}Al invoking a late introduction of SN ejecta has four significant shortcomings : (i) Not all stars form in large clusters and most clusters are dynamically unbound and disperse in ~ 10 Myr (Lada & Lada 2003). It is statistically unlikely that the Sun would have been sufficiently close to a massive star at the end of the latter's main sequence life (Williams & Gaidos 2007; Gounelle & Meibom 2008b). (ii) Even the most massive stars have a main sequence lifetime of at least 3 Myr and, if they and the Sun formed simultaneously, the former would have ended in supernovae late in the evolution of the solar nebula and probably long after CAIs containing the canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio had formed. These CAIs, the oldest dated solids from the Solar System (Amelin et al. 2002), have a narrow range of inferred initial $^{26}\text{Al}/^{27}\text{Al}$ ratios suggesting that they formed in $\ll 1$ Myr (Thrane et al. 2006; Jacobsen et al. 2008), consistent with the duration of Class 0-I stages of protostars (Smith 2004; Ward-Thompson et al. 2007). A short interval of CAI formation is also consistent with the nar-

row range of their oxygen isotope compositions ($\Delta^{17}\text{O} = -24 \pm 2\%$) (MacPherson et al. 2008; Makide et al. 2008), which are similar to the inferred oxygen isotopic composition of the Sun (Hashizume & Chaussidon 2005). [Later CAI formation would presumably have reflected the rapid oxygen isotopic evolution of the solar nebula along the slope-one carbonaceous chondrite anhydrous minerals (CCAM) line towards the terrestrial value ($\Delta^{17}\text{O} = 0\%$), a trend attributed to CO photochemical self-shielding and radial mixing in the disk (Yurimoto et al. 2007; Aléon et al. 2007).] (iii) Late injection of ^{26}Al into the protoplanetary disk would likely have disturbed the oxygen isotopic composition of the disk from the CCAM line, and this is not observed (Gounelle & Meibom 2007). (iv) SN models that produce the canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio invariably over-predict the abundance of ^{53}Mn and must impose fallback of the innermost layers, e.g., Meyer (2005). (These models also over-predict the abundance of ^{60}Fe , see §5.3).

A scenario in which SLRs from coeval SN progenitors were injected into the protoplanetary disk can be evaluated for its statistical plausibility. Gounelle & Meibom (2007) estimated that the probability that any given disk is contaminated by a SN with enough ^{26}Al to reach the canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio is $\leq 0.3\%$. However, there are three limitations to their model: (i) It underestimated the probability by assuming a maximum disk radius of 50 AU based on observations and theoretical arguments that disks within 0.1 pc of massive (O) stars suffer from photoevaporation (Johnstone et al. 1998; Chevalier 2000). But disks further from O stars are invariably larger (Vicente & Alves 2005; Andrews & Williams 2007; Balog et al. 2007) and this effect compensates the greater distance from the source of radionuclides. (ii) Their model overestimated the probability by neglecting the expansion of the host star cluster and using the ≤ 1 Myr-old Orion nebular cluster as a template, rather than a cluster at the minimum age (3 Myr) when supernovae occur. In older clusters, stars are more widely separated. (iii) It only included the contribution of SN to ^{26}Al . ^{26}Al is also produced and ejected from stars with initial masses $\geq 40 M_{\odot}$ in their Luminous Blue Variable (LBV) and Wolf-Rayet (WR) phases (Arnould & Prantzos 1986;

Palacios et al. 2005; Sahijpal & Soni 2006).

1.3. Was Solar System ^{26}Al inherited?

The uniform distribution of ^{26}Al , the existence of the canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio in CAIs, the adherence of primitive oxygen isotope compositions to the CCAM line, and the low likelihood of a SN injection event all point to the introduction of ^{26}Al before the collapse of the protosolar cloud. Indeed, the oxygen isotopic composition of the *entire* Solar System appears to be displaced from the locus of mean Galactic evolution (Young et al. 2008), suggesting primordial contamination. The source of ^{26}Al must also have introduced ^{41}Ca , which co-occurs with an inferred initial abundance of $^{41}\text{Ca}/^{40}\text{Ca} \sim 1.5 \times 10^{-8}$ (Sahijpal & Goswami 1998). The half-life of this radionuclide is only 0.1 Myr, limiting any time delay between production at the source and its incorporation into CAIs. The source of ^{26}Al cannot have been accompanied by substantial ^{53}Mn , as is the case of SN ejecta without fallback onto the remnant (Meyer 2005). (The predicted ^{53}Mn abundance in the interstellar medium is consistent with its inferred initial abundance in the Solar System and a “local” source is not required.) Any relationship between the source of ^{26}Al and that of ^{60}Fe remains to be determined. There is as yet no evidence that ^{60}Fe and ^{26}Al are correlated and had the same origin. Indeed, there may be a *deficit* of ^{60}Fe relative to ^{26}Al compared to SN ejecta that cannot be explained by free decay of the two radionuclides: The initial ratio of ^{60}Fe to ^{26}Al in the Solar System was 0.1–0.2 (Tachibana et al. 2006), lower than the 0.3 deduced from the Galactic average γ -ray emission (Wang et al. 2007) and theoretical predictions (Limongi & Chieffi 2006; Woosley & Heger 2007).

Very massive ($\geq 40 M_{\odot}$) stars eject ^{26}Al (and other SLRs) during the Wolf-Rayet phase of mass loss near the end of hydrogen core burning, as well as in SN (Arnould & Prantzos 1986). WR winds might account for a large fraction of the total fluence and Galactic distribution of γ -rays from the decay of ^{26}Al (Palacios et al. 2005; Diehl 2006; Voss et al. 2008; Martin et al. 2008). [The non-detection of γ -ray emission in the decay line of ^{26}Al from the nearest WR star γ^2 -Velorum can be explained by the dispersal of most of the radionuclide to large angular separa-

tion (Mowlavi & Meynet 2006)]. We propose that most or all of the ^{26}Al in the early Solar System originated in WR winds from one or more massive stars that contaminated the molecular cloud from which the Sun formed. (Sahijpal & Soni (2006) also considered the contribution of WR winds to Solar System inventories of SLRs.) These stars could have been members of the same embedded cluster as the Sun, or, more likely, members of another cluster that formed in the same giant molecular cloud (GMC) (Figure 1). An analogous “self-contamination” scenario has been invoked to explain anomalous abundance patterns in some globular clusters (Smith 2006).

Our proposal is based upon the following: (*i*) The amount of ^{26}Al ejected in the winds of a single 60 M_\odot star (Limongi & Chieffi 2006) is sufficient to contaminate $2 \times 10^4 \text{ M}_\odot$ of solar-metallicity gas to the canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio of the Solar System. (*ii*) The WR phase can occur as soon as 1-2 Myr after star formation and more than 1 Myr before the SN (Palacios et al. 2005), making it more likely to contaminate residual star-forming molecular gas. (*iii*) WR winds have speeds of up to 2000 km sec^{-1} (Niedzielski & Skórzynski 2002) and can traverse star-forming regions (10-100 pc) in $10^4 - 10^5$ yr. (*iv*) In contrast to single clusters where star-formation may be co-eval, star formation in a molecular cloud can occur over an interval of at least a few Myr (Hartmann et al. 2001), and possibly longer (Williams et al. 2000) as clumps of gas with a mass spectrum $M^{-1.7 \pm 0.1}$ (Pudritz 2002) form multiple embedded stellar clusters (Williams et al. 2000). For example, the Orion star-forming complex contains several subgroups that are several Myr older than the Orion nebula cluster (Bally 2008)(*v*) Wolf-Rayet winds contain multiple SLRs, including ^{26}Al , ^{41}Ca , and ^{36}Cl , but little or no ^{53}Mn or ^{60}Fe (Arnould et al. 2006). We propose that the collapse of the protosolar cloud homogenized the distribution of these isotopes (but see §5.2). Our scenario does not preclude a SN-triggered collapse (Cameron & Truran 1977; Boss 2008), which would have occurred *after* the WR phase.

In §2 we revisit the scenario of ^{26}Al -introduction by SN into the protoplanetary disk with a Monte Carlo approach that used more realistic disk sizes, accounted for the expansion of clusters, and included the contribution from both WR winds and

SN. While our results differ quantitatively from those of Gounelle & Meibom (2007), the calculated probability of a disk having the canonical Solar System $^{26}\text{Al}/^{27}\text{Al}$ ratio is nevertheless small (<2%). We also consider Bondi-Hoyle accretion of contaminated intracluster gas, as proposed by Throop & Bally (2008) and find its inclusion does not significantly alter this result (§3). We then use a similar Monte Carlo model to investigate a scenario where ^{26}Al is introduced by WR winds into the parent molecular cloud of the Sun (§4). This model readily reproduces the canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio of the Solar System. We discuss the delivery of ^{26}Al from WR winds into the molecular cloud, interpret CAIs that lack the canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio, and, in the context of the cloud contamination scenario, present additional calculations for three other SLRs (^{41}Ca , ^{60}Fe , and ^{36}Cl) in §5.

2. Disk contamination scenario

We calculated the Galactic distribution of $^{26}\text{Al}/^{27}\text{Al}$ ratio in the disk injection scenario (Ouellette et al. 2005) by extending the model of Williams & Gaidos (2007) to include ^{26}Al from both winds and SN, a dynamically realistic description of cluster expansion, and the effect of the UV field of massive stars on disk size. Unlike Williams & Gaidos (2007) we do not explicitly consider disk evolution and disappearance in our model because this occurs on a timescale of ~ 6 Myr (Haisch et al. 2005), much longer than the likely epoch of CAI formation.

For simplicity, we assume that every young low-mass star has a disk and that the properties of the disk are independent of stellar mass. According to Lada & Lada (2003), 72% of stars form in clusters with $N_* > 100$ members distributed in size according to $dN_c/dN_* \propto N_*^{-2}$. The remaining 28% form in isolation or in clusters with fewer than $N_* = 100$ stars. The most massive members of such small clusters will be $\sim 5 \text{ M}_\odot$ B stars that do not produce winds or Type II core-collapse SN. Disks around members of such clusters will not receive any exogenous ^{26}Al . The other 72% of disks were represented by 10^5 Monte Carlo calculations. The size of the host cluster of each disk was drawn from a N_*^{-1} distribution ($N_* \geq 100$). The number of massive stars (SN progenitors with $M_* > 8\text{M}_\odot$) in the host cluster was

selected from a Poisson distribution with an average of $3 \times 10^{-3} N_*$ (Williams & Gaidos 2007). The masses of these stars were drawn from a power-law initial mass function $dN_*/dM_* \propto M_*^{-2.5}$ (Kroupa 2002). Clusters form over ~ 1 Myr (Hillenbrand et al. 2007) and most star formation in a single cluster occurs within ~ 3 Myr (Hartmann 2001; Hartmann 2003; Huff & Stahler 2006; Jeffries 2007; Hillenbrand et al. 2007). We assumed the instantaneous formation of all massive stars and an exponentially decaying rate of low-mass star formation after massive star formation. We used age statistics for members of the Orion Nebula Cluster (Palla & Stahler 1999) to infer a decay time of 2.7 Myr, which we adopted for clusters of all sizes. We assumed that the rate of star formation does not depend on stellar mass.

The $^{26}\text{Al}/^{27}\text{Al}$ ratio in the disk around the i -th low-mass star at an interval T after the star's formation at time t_i^* was calculated by summing over the product of the yield m_j of the radionuclide from the j -th wind or SN, the solid angle subtended by the disk at the time of ejection t_j , and the factor of free decay between that time and $t_i^* + T$;

$$(^{26}\text{Al}/^{27}\text{Al})_i = \frac{r_d^2}{8m_d f_{Al}} \Sigma_j \frac{m_j}{d_{ij}^2} \exp [\log 2(t_j - t_i^* - T)/\tau_{1/2}] \quad (1)$$

where r_d and m_d are the (constant) radius and mass of the disk, f_{Al} is the mass fraction of ^{27}Al , and d_{ij} is the distance of the disk from the source star during the at the time of ejection. We considered injection as instantaneous because the speeds of SN ejecta and winds are $> 1000 \text{ km s}^{-1}$, and the ^{26}Al -producing WR phase of an individual massive star is brief (~ 1 Myr) compared to the dispersal timescale of the cluster (~ 10 Myr). To account for the changing perspective of each star as it orbits inside the cluster, we used the isotropic average of the projected cross-section of each disk, $\pi r_d^2/2$. m_j and t_j were estimated by spline interpolation in a grid of yield calculations by Limongi & Chieffi (2006). We used a default disk radius of 200 AU (Vicente & Alves 2005; Andrews & Williams 2007) but to account for photoevaporation by the UV radiation from massive stars (Johnstone et al. 1998) we reduced this to 30 AU for disks within 0.2 pc of the cluster center at 3 Myr, and to zero for disks within

0.1 pc. This was a conservative assumption, since the evidence for significant disk truncation is weak (Balog et al. 2007), but it only has a minor effect on our results. Like Ouellette et al. (2005), we adopted a Minimum Mass Solar Nebula disk mass of 0.013 M_\odot and the fractional abundance of ^{27}Al given by Lodders (2003).

As in Williams & Gaidos (2007), we placed the massive stars at the cluster center (Grebel 2007) and assumed that, at any time, low-mass stars were distributed with an inverse-square density profile, such that an equal number of stars reside in shells of constant thickness out to the edge of the cluster at r_c . To model cluster expansion, and thereby determine the distance of a disk to each source of ^{26}Al , we developed an empirical relationship for the time dependence of r_c based on a series of numerical simulations of clusters containing between 100 and 15,000 stars. The dynamical simulations were preformed using the NBODY4 code running on the Cambridge University GRAPE-6a card (Aarseth 2003). In each case the stars were initially (3 Myr) distributed in a Plummer sphere (Binney & Tremaine 1988) with a radius set by the requirement that the initial surface density $\Sigma_3 = 100 \text{ pc}^{-2}$ (Williams & Gaidos 2007). The virial parameter Ω (ratio of kinetic to gravitational potential energy) was set to 1.5. This condition is brought about by a cluster local star formation efficiency of 33% in the embedded cluster and the instantaneous removal of the remaining gas at 3 Myr (Bastian & Goodwin 2006). The size of the cluster was explicitly determined at regular intervals until an age of 10 Myr. We found that the expansion of the cluster from its size at 3 Myr was closely approximated by

$$r_c(t) \approx r_c(3 \text{ Myr}) + 0.45 \left[2G\bar{M}_*\Omega\sqrt{\pi\Sigma_3 N_*} \right]^{1/2} (t - 3 \text{ Myr}), \quad (2)$$

where G is the gravitational constant and \bar{M}_* is the average stellar mass. The expression multiplying 0.45 is the cluster's virial speed (Binney & Tremaine 1988). In each of our simulations the surface density of the cluster fell to the background level of field stars ($2-3 \text{ pc}^{-2}$) by 10 Myr, in agreement with observations (Lada & Lada 2003).

Eqn. 2 specifies the radius of the cluster at the epoch t_j of a massive stellar wind or SN. The uniform distribution of low-mass stars with dis-

tance from the cluster center $0 < d_{ij} < r_c(t_j)$ was then used in Eqn. 1 to produce a distribution of $^{26}\text{Al}/^{27}\text{Al}$. These distributions were summed over all events in a cluster, corrected for free decay, averaged over 10^5 realizations, and multiplied by 0.78 to produce a Galactic distribution.

The calculated distributions of $^{26}\text{Al}/^{27}\text{Al}$ are plotted in Figure 2 and the fractions of systems that have any initial ^{26}Al or ^{26}Al abundances exceeding the canonical value are given in Table 1. We also report the 95-percentile values of $^{26}\text{Al}/^{27}\text{Al}$. We considered two values for T , which in the Solar System represents the epoch of CAI formation. The probability is 1.1% for $T = 0.5$ Myr, rising to 1.9% by 1 Myr. The probability is higher at still later, but unlikely CAI formation times (not shown). Our probabilities are several times higher than that reported by Gounelle & Meibom (2008), mostly due to the larger disk size we used, but are still small. Our estimates are nonetheless optimistic because we assume all high-mass stars form prior to low-mass stars. If all stars form instantaneously, then nearly 3 Myr must elapse before ^{26}Al is produced, and *no* disks contain ^{26}Al by the time of CAI formation.

3. Bondi-Hoyle accretion scenario

Disks might also accrete gas from their natal cluster before it is removed by winds and SN explosions. Throop & Bally (2008) proposed that Bondi-Hoyle accretion of residual, SN-contaminated cluster gas onto the protosolar nebula produced isotopic anomalies in the Solar System, including the presence of SLRs. They estimated that disks around solar-mass stars in a 3000-star cluster could accrete an additional $\sim 0.01 M_\odot$ of gas, an amount comparable to the original mass of a disk, over the 2-4 Myr that gas remained in the cluster. We estimated the amount of ^{26}Al that could be introduced by this process by specifying the fraction of disk mass f acquired by Bondi-Hoyle accretion by the time of CAI formation, and assuming that accretion is constant as long as intracluster gas is present. We assumed that the maximum amount of mass that can be accreted by a disk is equal to the initial disk mass (Throop & Bally 2008), i.e. $f \leq 0.5$. To account for the absence of cluster gas during the history of later-forming stars we adjusted the

accreted mass by the ratio of the time interval between low-mass star formation and the disappearance of cluster gas, and the lifetime of the cluster gas. Like Throop & Bally (2008), we assumed a gas lifetime of 3 Myr. We calculated the average $^{26}\text{Al}/^{27}\text{Al}$ ratio of cluster gas during the period of Bondi-Hoyle accretion (see §4 for details) and then determined the final $^{26}\text{Al}/^{27}\text{Al}$ of the disk as $^{26}\text{Al}/^{27}\text{Al} = (1-f)(^{26}\text{Al}/^{27}\text{Al})_0 + f(^{26}\text{Al}/^{27}\text{Al})_{acc}$ where the subscripts refer to the initial value and the average value during accretion.

We calculated distributions of the $^{26}\text{Al}/^{27}\text{Al}$ ratio for combined Bondi-Hoyle accretion and disk injection and found that the former has a negligible effect (Figure 2 and Table 1). This is because low-mass stars that form late enough (~ 3 Myr) to acquire significant ^{26}Al will accrete little gas because the intracluster gas disappears soon thereafter. This is of course entirely a result of our (reasonable) assumption that intracluster gas is evacuated by the time the massive stars leave the main sequence, if not earlier. Nevertheless the same cosmochemical timing arguments that apply to the disk injection scenario also apply to the Bondi-Hoyle scenario; CAIs probably formed by the time a disk had formed, or very soon thereafter, and thus later accretion of contaminated gas cannot be responsible for the presence of ^{26}Al in them.

4. Molecular cloud contamination scenario

In this scenario the Sun's natal giant molecular cloud spawned an earlier generation of massive stars [Figure 1(a)] whose WR winds contaminated the rest of the cloud (b), from which the Sun subsequently formed, perhaps in a second cluster (c and d). We calculated the distribution of $^{26}\text{Al}/^{27}\text{Al}$ ratios in this scenario by 10^5 Monte Carlo simulations, each corresponding to a disk formed from a GMC contaminated by an immediately previous generation of massive cluster stars. The number and masses of those stars were drawn from the distributions described in §2. The mass of gas in the GMC was calculated using an average stellar mass derived from the initial mass function of Kroupa (2002), and a total star-formation efficiency of 10% (Williams et al. 2000). The amount of ^{26}Al added to the molecular cloud by massive stellar winds was calculated as a function of time

using the yields and times of Limongi & Chieffi (2006) and by assuming 100% delivery efficiency and instantaneous mixing into the cloud (we discuss this assumption further in §5.1). We did not include SN ejecta in these calculations, but include it when we consider ^{60}Fe in §5.3 (but see the footnote on SN ejecta delivery in §5.1). We assumed that the Sun and CAIs formed simultaneously.

We first carried out a series of calculations for different intervals of elapsed time (3-6 Myr) between the formation of the earlier generation of massive stars and the Sun (dashed lines in Figure 3). If the interval is less than 3 Myr contamination has yet to take place in our model and newly-formed stellar systems lack ^{26}Al . An interval of 4-5 Myr is most likely to produce the CAI value. The history of low-mass star formation in molecular cloud complexes is poorly known but clearly non-monotonic (Hartmann et al. 2001; Hartmann 2003). We calculated more realistic distributions by again adopting the exponential rate with a 2.7 Myr decay time based on the data of Palla & Stahler (1999). This is plotted as the heavy solid line in Figure 3. That curve can be understood as a convolution of the star formation history with the $^{26}\text{Al}/^{27}\text{Al}$ distributions for “starburst” scenarios. The probability of $^{26}\text{Al}/^{27}\text{Al}$ exceeding the canonical value is 6.2%. This figure depends on the assumed star formation history: For example, varying the decay time constant by ± 1 Myr changes the fraction between 4.3 and 6.5%. However, the peaks in all three distributions are near the CAI value (solid lines in Figure 3). This robustness is a result of negligible ^{26}Al production at times earlier than 3 Myr and negligible low-mass star formation at times much later than 5 Myr. We found that simulations which produce a $^{26}\text{Al}/^{27}\text{Al}$ ratio within 2σ [$\sigma = 0.1 \times 10^{-5}$ (Goswami et al. 2005)] of the canonical value were most likely to involve contamination of a GMC having $\sim 3 \times 10^5 M_\odot$ of gas by the massive members of a cluster with $\sim 10^5$ stars. Such a situation is exemplified in our galaxy by NGC 3603, which contains multiple Wolf-Rayet stars within an HII region (Melena et al. 2008).

5. Discussion

5.1. Delivery of ^{26}Al into the molecular cloud

Our scenario requires a plausible mechanism for the efficient introduction of the ^{26}Al carrier in Wolf-Rayet winds into the surrounding molecular cloud. In the calculations above, we assumed a 100% delivery efficiency but this will clearly not be the case. In general, mixing between the hot, tenuous gas from massive stars and cooler, denser molecular gas is thought to be very inefficient (de Avillez & Mac Low 2002). SN-enriched gas from HII regions is thought to find its way back into the interstellar medium (if at all) through a circuitous route taking ~ 100 Myr (Tenorio-Tagle 2000). Impact of SN ejecta onto a protostellar cloud core may induce mixing via Rayleigh-Taylor and Kelvin-Helmholtz instabilities (Boss & Foster 1998; Boss 2008) but the injection efficiency is too low to explain the Solar System’s canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio¹. Gas in Wolf-Rayet winds will be less dense than SN ejecta by several orders of magnitude and efficient mixing in the gas phase is even less likely. Instead, the high-velocity (500-2000 km sec $^{-1}$) winds will develop a reverse shock upon encountering the much denser molecular cloud (Weaver et al. 1977).

We propose that refractory dust grains are the principle carrier of ^{26}Al and ^{41}Ca in Wolf-Rayet winds and that these can dynamically decouple from the shocked wind and imbed themselves into the surrounding molecular cloud, analogous to the “aerogel” model described by Ouellette et al. (2005). Pre-solar grains of Al_2O_3 (corundum or other forms) are found in primitive meteorites but their oxygen isotopes indicate a source in red giant or AGB stars, not in very massive stars (Hutcheon et al. 1994; Ott 2007; Nittler et al. 2008). Although many of these grains have large ^{26}Mg excesses produced by the decay of ^{26}Al , the abundance of these grains is

¹Adopting an ^{27}Al mass fraction of 5.8×10^{-5} (Lodders 2003), the protosolar cloud core initially contained $3 \times 10^{-9} M_\odot$ of ^{26}Al . The mass fraction of ^{26}Al in the convective hydrogen shell of a $25 M_\odot$ star at the end of its main-sequence life is $\sim 1 \times 10^{-6}$ (Meyer 2005). Therefore *at least* $3 \times 10^{-3} M_\odot$ of SN ejecta must have been introduced (assuming no free decay). Boss et al. (2008) report that only $5 \times 10^{-5} M_\odot$ is injected in their model.

insufficient to account for the canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio (Hutcheon et al. 1994). In fact, the ^{26}Al in CAIs must have been processed through the gas phase and subsequently recondensed into the refractory inclusions. The pre-solar grains are also much larger ($\sim 1 \mu\text{m}$) than the silicate grains predicted to form from winds and ejecta. Their size may be why they survived the incorporation process and the latter did not.

Simple models of grain nucleation and growth predict oxide grain growth to sizes of 0.01-0.1 μm in SN ejecta (Nozawa et al. 2007). SN are predicted to be copious sources of dust, but observations have so far produced evidence only for a few times $10^{-5} M_{\odot}$ of dust in individual events (Meikle et al. 2007). Dust production in WR stars is poorly investigated, although such stars appear to be minor contributors to the over-all interstellar dust budget (Tielens et al. 2005). Copious amorphous carbon dust is observed around carbon-rich Wolf-Rayet CO stars and is thought to be the result of colliding stellar winds in binary systems (Crowther 2003). WCO stars do *not* produce ^{26}Al , but dust production by predecessor LBV and WN phases predicted to contain ^{26}Al in their winds has recently been established (Rajagopal et al. 2007; Barniske et al. 2008). The η Carinae LBV star ejected $\sim 10 M_{\odot}$ of dust-rich material during its 1843 eruption (Smith et al. 2003), including aluminum oxide (de Koter et al. 2005), although its ^{26}Al content has yet to be definitely established by γ -ray observations (Knödlseder et al. 1996).

To reach the molecular cloud, grains must survive sputtering after they pass the reverse shock and move at high-speed ($\sim 10^3 \text{ km sec}^{-1}$) with respect to the shocked gas in the HII region. They also must not be completely decelerated within the reverse shock zone. These conditions place a lower limit on grain size. Grains too small are sputtered to destruction or eventually vaporized in the hot, shocked gas (Nozawa et al. 2007). The density of the wind 1 pc from a Wolf-Rayet star losing mass at a rate of $10^{-5} M_{\odot} \text{ yr}^{-1}$ is $\sim 10^{-2} \text{ cm}^{-3}$ and the stopping distance of grains even as small as $0.01 \mu\text{m}$ grains is 10 pc, comparable or larger to the size of HII regions. The deceleration across the scale of the shocked region ($\sim 1 \text{ pc}$) (Weaver et al. 1977) will be low and the fraction of material sputtered from the grains, which is re-

lated to the deceleration [Eqn. 1 in Nozawa et al. (2007)] will be likewise small².

Grains that escape the WR wind will not penetrate far into a GMC. Typical hydrogen number densities in clouds are $10^2 - 10^3 \text{ cm}^{-3}$ and the stopping distance of $0.01\text{-}0.1 \mu\text{m}$ grains will be only of order $\sim 10^3 \text{ AU}$. Gas densities in portions of the molecular cloud that are shocked and swept up by the expanding wind or SN ejecta will be higher and the stopping distances proportionally shorter. Thus, only the surfaces of clouds will be initially contaminated by ^{26}Al . Further transport of dust grains into cloud depends on their kinematics, which are poorly understood. The smallest scale on which turbulence in clouds can affect the mass distribution and cause mixing is the sonic transition where the turbulent velocity is equal to the sound speed; this is roughly 1 pc in solar-metallicity clouds (Padoan 1995). Thus mixing might be inefficient at the surfaces of clouds. The degree to which this controls the incorporation of ^{26}Al into new low-mass stars depends on the extent of large-scale mixing and whether star formation is triggered or at least assisted, by the interaction of winds or SN ejecta with cloud gas (Zavagno et al. 2007). In that case, star formation is spatially correlated with ^{26}Al abundance.

Wolf-Rayet progenitors may themselves migrate into and contaminate regions of a molecular cloud where low-mass star formation has yet to occur. 10-30% of O stars have large peculiar velocities (up to 200 km sec^{-1}) relative to most early-type stars as a result either of dissolution of binary systems by SN explosions, or encounters between two binary systems (Hoogerwerf et al. 2001). One of these so-called “runaway” O stars moving at a typical speed of 30 km sec^{-1} would traverse a molecular cloud in $\sim 1 \text{ Myr}$. Mass loss from this star, if occurring, could contaminate a larger region of the molecular cloud with SLRs.

²In contrast, the density of shocked SN ejecta is $\sim 10^5 \text{ cm}^{-3}$, the stopping distance of a $0.1 \mu\text{m}$ grain is only $\sim 2 \text{ AU}$, whereas the ejecta scale length can be as large as 1 pc. Thus grains in SN ejecta are more likely to be trapped in the ejecta and never introduced into star-forming molecular gas. This is another argument for WR winds as the source of ^{26}Al in the Solar System.

5.2. CAIs with low initial $^{26}\text{Al}/^{27}\text{Al}$ ratios

Any scenario that explains the canonical Solar System $^{26}\text{Al}/^{27}\text{Al}$ ratio must also accommodate the exceptions. Several classes of CAIs show either no excess of ^{26}Mg produced by the decay of ^{26}Al or have an inferred $^{26}\text{Al}/^{27}\text{Al}$ ratio $\ll 1 \times 10^{-5}$, much lower than the canonical value of $(4.5\text{-}5) \times 10^{-5}$. These include (*i*) igneous CAIs associated with chondrule-like materials (relict CAIs inside chondrules and CAIs surrounded by chondrule-like, ferromagnesian silicate rims) (Krot et al. 2005a; Krot et al. 2005b); (*ii*) some igneous CAIs in metal-rich (CB and CH) carbonaceous chondrites (Gounelle et al. 2007; Krot et al. 2008b); (*iii*) FUN (fractionation and unidentified nuclear effects) CAIs (Lee 1988), (*iv*) isolated platy hibonite crystals (PLACs) (Ireland & Fegley 2000), (*v*) pyroxene-hibonite spherules (Ireland et al. 1991; Russell et al. 1998); (*vi*) some corundum-bearing CAIs (Simon et al. 2002), and (*vii*) most of the grossite- and hibonite-rich inclusions in CH chondrites (Kimura et al. 1993; Weber et al. 1995; Krot et al. 2008b).

(*i* and *ii*): CAIs associated with chondrule materials and some igneous CAIs in CB and CH carbonaceous chondrites (Krot et al. 2001, 2005a,b, 2008b) are ϕ_{16} -depleted to varying degrees ($\Delta^{17}\text{O}$ ranges from $-25\text{\textperthousand}$ to $-5\text{\textperthousand}$) relative to typical CAIs in primitive chondrites which uniformly have ^{16}O -rich compositions ($\Delta^{17}\text{O} \sim -25\text{\textperthousand}$) (Itoh et al. 2004; Makide et al. 2008). We infer that the ^{26}Al -poor and ϕ_{16} -depleted CAIs experienced late-stage melting and oxygen isotope exchange, probably during chondrule formation, which could have reset their $^{26}\text{Al}-^{26}\text{Mg}$ systematics.

(*iii-vii*): The lower than the canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio in FUN CAIs, PLACs, pyroxene-hibonite spherules, some corundum-bearing CAIs, and most of the grossite- and hibonite-rich inclusions in CH chondrites can be explained by (a) their late formation, after decay of ^{26}Al , (b) their early formation, prior to introduction of ^{26}Al , or (c) the lack of the canonical budget of ^{26}Al in their precursors. Most of these CAIs have ϕ_{16} -rich compositions (Goswami et al. 2001; Simon et al. 2002; Krot et al. 2008b; Krot et al. 2008c), indistinguishable from those of typical CAIs with the

canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio. The rapid evolution of the oxygen isotopic composition of the inner Solar System (Krot et al. 2005c; Aléon et al. 2007) and the short ($< 10^5$ yr) duration of CAI formation (Thrane et al. 2006; Jacobsen et al. 2008) thus make (a) unlikely. Similar arguments can be used against (b). Although an early formation is possible if complete melting and exchange of oxygen isotopes occurred, this seems unlikely considering evidence for incomplete melting of CAIs (MacPherson et al. 2005).

We infer that the CAIs of categories *iii-vii* formed contemporaneously with ^{26}Al -rich inclusions. The absence of canonical ^{26}Al in their precursors suggests either they formed prior to homogenization of ^{26}Al in the Solar System (Sahijpal & Goswami 1998; Krot et al. 2008b; Krot et al. 2008c) or preferential loss of the (uniformly distributed) ^{26}Al carrier during thermal processing of the CAI precursors (Wood 1996). Both explanations can be reconciled with the presence of nucleosynthetic anomalies in some of these CAIs (Lee et al. 1998) if the ^{26}Al carrier contributed a distinct component to the Solar System's stable isotope composition (Lee et al. 1998). The second explanation is more speculative, however. It hypothesises that (a) the precursors of these CAIs were isotopically heterogeneous and, contrary to typical refractory inclusions, escaped a cycle of complete evaporation-condensation, (b) the carrier of ^{26}Al was relatively volatile, and (c) it was lost to varying degrees by sublimation of these CAI precursors prior to their melting. Although these inclusions can be used as an evidence for heterogeneous distribution of ^{26}Al among CAI precursors, the scale of any heterogeneity was probably limited because such inclusions are rare relative to ^{26}Al -rich CAIs.

5.3. Other SLRs

^{41}Ca : A further test of the wind model is whether it can also reproduce the inferred initial $^{41}\text{Ca}/^{40}\text{Ca}$ ratio of 1.5×10^{-8} (Sahijpal & Goswami 1998). Published calculations of ^{41}Ca yields in winds from massive stars are limited. We considered a 60 M_\odot progenitor for which ^{41}Ca and ^{26}Al yields from the Wolf-Rayet winds were separately published (Arnould et al. 2006; Limongi & Chieffi 2006). We accounted for the additional free decay of ^{26}Al , which is ejected during the hydrogen-burning WN

Wolf-Rayet phase, while ^{41}Ca is produced in the later core He-burning WCO phase 1.9×10^5 yr later. The corrected ratio of ^{41}Ca to ^{26}Al in the ejecta is ~ 25 times higher than in the Solar System, but would be consistent if an additional time $\Delta \approx 0.5$ Myr elapsed before CAI formation. It is interesting that this is approximately the same duration as the Wolf-Rayet phase itself before the final SN Ib/c.

^{60}Fe : Wolf-Rayet winds contain negligible amounts of ^{60}Fe (Arnould et al. 2006). Live ^{60}Fe in the early Solar System could have originated in SN from the same early generation of massive stars that produced the ^{26}Al , or in an even earlier generation of stars (Gounelle & Meibom 2008a). We repeated the calculations described in §4 but included SN contributions and calculated $^{60}\text{Fe}/^{56}\text{Fe}$ ratios in the same manner as $^{26}\text{Al}/^{27}\text{Al}$, using the yields of Limongi & Chieffi (2006) and the solar iron abundance of Lodders (2003). We assume $\Delta = 0.5$ Myr based on the ^{41}Ca abundance. In Figure 4 we plot Monte Carlo realizations for different epochs (3–8 Myr before the Sun) for the earlier generation of massive stars. If all SN ejecta is incorporated, the $^{60}\text{Fe}/^{56}\text{Fe}$ is over-predicted by an order of magnitude relative to $^{26}\text{Al}/^{27}\text{Al}$. A comparison with the ratio of the two SLRs (black line) inferred from γ -ray measurements (Wang et al. 2007) suggests that this discrepancy may be in part the result of an overprediction of ^{60}Fe yield - or underprediction of ^{26}Al yield - by the nucleosynthesis models (see §6). There are two other explanations suggested by Figure 4: (a) the Sun formed 3 Myr after the massive stars, when many massive stars were in the WR phase but few SN had occurred (a scenario represented by the red dots extending below the primary locus); or (b) the SN contribution was attenuated by an effect such as described in §5.1.

Explanation (a) is statistically unlikely if star formation is uncorrelated and demands precise timing between the formation of massive stars and the Sun (~ 3 Myr later), but could be demanded in a scenario where the Sun's formation was triggered by a SN (Cameron & Truran 1977; Boss 2008). Our simulations indicate that the initial solar $^{26}\text{Al}/^{27}\text{Al}$ and $^{60}\text{Fe}/^{56}\text{Fe}$ ratios can be reproduced in this manner only in star clusters with $N_* > 10^5$ whose most massive members have $\sim 100 \text{ M}_\odot$. As such large clusters are relatively rare, this scenario

is *a priori* less likely. Explanation (b) requires a reduction in the SN contribution to ^{60}Fe (and ^{26}Al) by a factor of 20. This could be due to a combination of effects; retention or fallback of the central region of the progenitor (Meyer 2005), inefficient delivery of SN ejecta into the cloud (§5.1) or the collapse of the protosolar cloud and a decrease in its cross-section by the time the SN ejecta arrived. An alternative scenario (c) is that ^{60}Fe in the Solar System is the relict of an even earlier episodes of massive star-formation and contamination (Gounelle & Meibom 2008a) of which the ^{41}Ca and most ^{26}Al has decayed. ^{60}Fe will decay to 5% of its initial abundance in 6.5 Myr, during which ^{26}Al decays to 0.2%, and ^{41}Ca essentially vanishes. This last explanation is viable only if this earliest generation of stars ceased to contribute SLRs to the molecular cloud after ~ 6 Myr.

^{36}Cl : We estimated the abundance of ^{36}Cl , which is also ejected by WR stars during the WCO phase (Arnould et al. 2006), and calculated the $^{36}\text{Cl}/^{37}\text{Cl}$ ratio in the same manner as $^{41}\text{Ca}/^{40}\text{Ca}$. We find that our model underpredicts the ratio by at least three orders of magnitude. It has already been recognized that stellar nucleosynthetic models cannot account for this isotope, especially if it was introduced at the epoch of CAI formation 1–2 Myr before the host sodalite alteration phases were formed. At the present time, the only viable explanation appears to be a late episode of irradiation by energetic particles (Hsu et al. 2006)

6. Summary and Outlook

The canonical abundance of ^{26}Al in the Solar System cannot be explained in terms of a late injection of debris from a nearby SN into the gaseous protoplanetary disk because (i) the dispersal of the natal cluster and the finite time window for injection make it *a priori* an unlikely event (<2%), (ii) ^{26}Al was already present in CAIs, which formed within $\sim 10^5$ yr of the initial collapse of the protosolar nebula and the formation of the protoplanetary disk, and (iii) the oxygen isotope systematics of primitive Solar System materials show no sign of a late introduction of SN ejecta. The apparently uniform distribution of ^{26}Al in meteorites and samples of the Earth, Moon, and Mars suggests homogenization during the collapse of the protosolar cloud.

We showed that the canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio can be explained if the Solar System formed from a molecular cloud contaminated by Wolf-Rayet winds from massive stars that formed 4-5 Myr earlier. A SN contribution is not required to explain the abundance of ^{26}Al , although it is not necessarily excluded. The *a priori* probability that such a level of contamination occurred depends on the poorly-understood star formation histories in GMCs; we estimate that it is $\sim 6\%$. However, our model predicts that the canonical value is close to the *most likely non-zero value* in the Galactic distribution.

The initial $^{41}\text{Ca}/^{40}\text{Ca}$ ratio can also be explained by Wolf-Rayet wind contamination if ~ 0.5 Myr elapsed between its introduction by winds and the formation of CAIs. If this scenario is also to explain primordial ^{60}Fe in the Solar System, the cloud must have been contaminated with SN ejecta as well. If SN ejecta is included, our model over-predicts the abundance of ^{60}Fe by an order of magnitude. This discrepancy could be rectified by some combination of the following: (a) most ^{60}Fe falls back onto SN remnants rather than be ejected (Meyer 2005; Takigawa et al. 2008); (b) most dust grains in SN ejecta are retained and destroyed in the shocked ejecta and never enter the molecular cloud; (c) the protosolar cloud was already collapsing and presented a smaller cross-section when the SN ejecta arrived; and (d) the ^{60}Fe is a relict of an even earlier episode of massive star formation and contamination for which all the other SLRs have decayed away. Absence of a significant excess of ^{53}Mn seems to require (a), but not to the exclusion of the other explanations. Our model does *not* explain the inferred abundance of ^{36}Cl , and another mechanism such as irradiation much be invoked.

A key uncertainty in our model is the efficiency with which ^{26}Al is introduced into the host molecular cloud and the degree to which it becomes uniformly mixed. We propose that the carrier of ^{26}Al was dust grains and that these dynamically decoupled from the wind and embedded themselves (intact) into the cloud, but this hypothesis needs further investigation. Furthermore, our model does not account for the inhomogeneities in SN ejecta and WR winds that could produce spatial variation in the contamination of a molecular cloud. There are also uncertainties in calculations of the

evolution and nucleosynthesis of massive stars that could quantitatively alter our results. Production of ^{26}Al by neon burning during the Type Ib/c SN that follows the Wolf-Rayet phase is sensitive to the progenitor mass (Higdon et al. 2004) and for a 60 M_\odot progenitor, could be as large as the yield from the wind (Woosley & Heger 2007). New models that include stellar rotation predict higher yields of ^{26}Al , an earlier appearance of ^{26}Al in the WR wind (as early as 1 Myr), and a smaller minimum initial mass for entry into the WR phase (Palacios et al. 2005). Larger ^{26}Al yields would relieve the requirement for high delivery efficiency to the molecular cloud and may resolve the discrepancy between the predicted amount of concomitant ^{60}Fe from SN ejecta and the inferred initial abundance of the radionuclide in the Solar System. Future tests of this model could compare predicted WR stellar contamination with short-lived isotopes (e.g., ^{107}Pd) whose abundances seem consistent with models of the interstellar medium (G. Huss, pers. comm.), as well as the Solar System's oxygen isotopic composition.

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TABLE 1
STATISTICS OF ^{26}Al ABUNDANCE IN DIFFERENT SCENARIOS

Scenario	%	$^{26}\text{Al}/^{27}\text{Al}$	
	> 0	$\geq 5 \times 10^{-5}$	95%
Disk injection:			
T = 0.5 Myr	16	1.2	5×10^{-6}
T = 1 Myr	20	1.9	1.3×10^{-5}
Disk injection with Bondi-Hoyle accretion			
T = 0.5 Myr	16	1.2	8×10^{-6}
T = 1 Myr	21	1.9	1.6×10^{-5}
Molecular gas contamination (T=0):			
2.7 Myr exp. SF	16	6.2	9×10^{-5}
1.7 Myr exp. SF	8	4.3	6×10^{-5}
3.7 Myr exp. SF	21	6.5	9×10^{-5}

NOTE.—Only simulations which produced ^{26}Al -contaminated systems are reported.

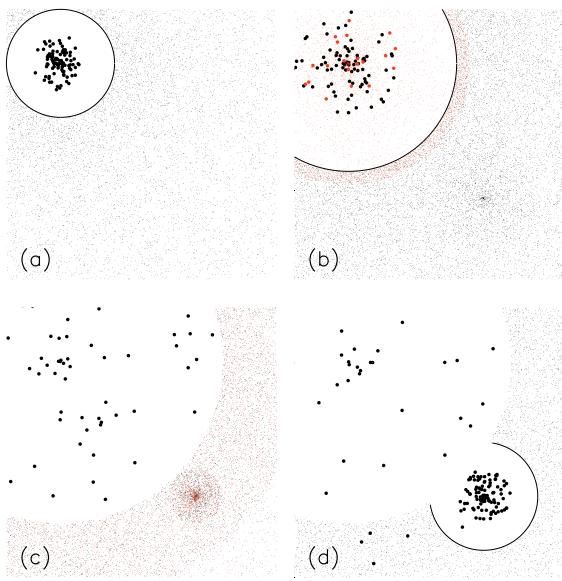


Fig. 1.— Cartoon of the molecular cloud contamination scenario to explain the presence of ^{26}Al in the early Solar System: (a) A young cluster of stars forms an HII region in a giant molecular cloud; (b) massive stars eject ^{26}Al into the cloud; (c) a clump collapses from the contaminated cloud; (d) a second generation of stars (including the Sun) forms from the clump.

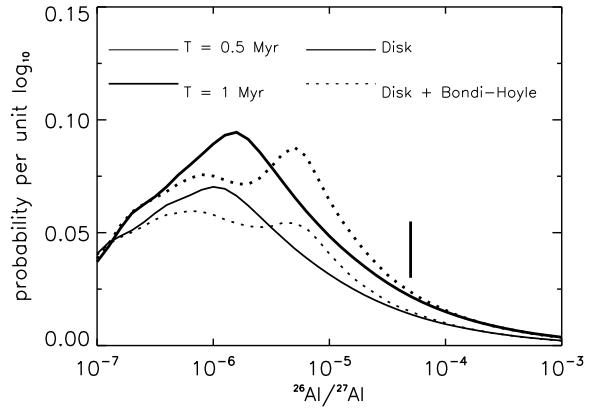


Fig. 2.— The distribution of non-zero values of the $^{26}\text{Al}/^{27}\text{Al}$ ratio predicted by a Monte Carlo model of its formation in massive stars and incorporation injection into the protoplanetary disk (see text for details). The units of the ordinate are fractional number of Monte Carlo systems per unit common logarithm. The vertical bar demarks the canonical Solar System value of 5×10^{-5} . The curves do not integrate to unity because a large majority of systems are not contaminated with ^{26}Al (Table 1). The solid curves are for the disk injection scenario (see text), and the dashed curves include Bondi-Hoyle accretion of nebular gas. Two values for the elapsed time between the formation of the Sun and ^{26}Al -containing CAIs are considered.

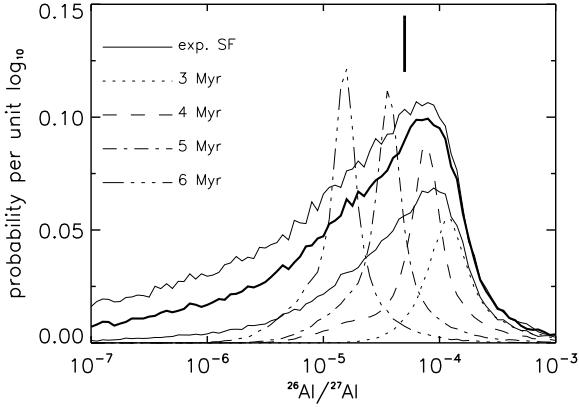


Fig. 3.— The distribution of non-zero values of the $^{26}\text{Al}/^{27}\text{Al}$ ratio predicted by an alternative model in which ^{26}Al was produced in an earlier generation of massive stars and introduced by Wolf-Rayet winds into the molecular cloud that formed the Sun (see text for details). The units of the ordinate are fractional number of Monte Carlo systems per unit common logarithm. The vertical bar is the canonical Solar System value of 5×10^{-5} . The integral of the curves are not unity because the majority of systems are not contaminated with ^{26}Al (Table 1). The broken curves are for a monotonic elapsed time between the formation of the earlier generation of massive, ^{26}Al -producing stars and the Sun. The solid curves (shown one-tenth scale) are for an exponentially-decaying rate of star formation with a decay time of 2.7 Myr (heavy curve) or 1.7 and 3.7 Myr (light curves). The area under the solid curves changes with assume star formation history, but the location of the peak does not.

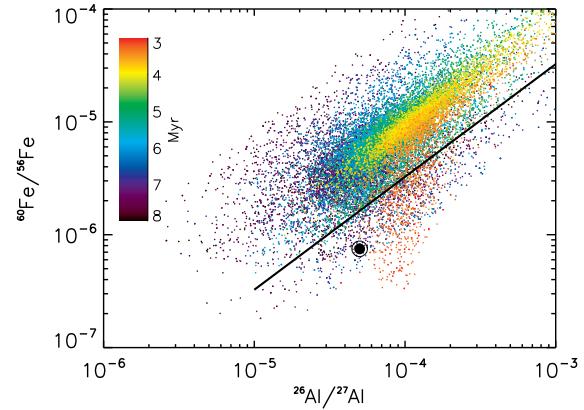


Fig. 4.— Calculated abundances of ^{26}Al and ^{60}Fe relative to stable comparison isotopes in star-forming regions contaminated by Wolf-Rayet winds and SN ejecta (see text for details). Each point represents a Monte Carlo calculation of the composition of the gas in a well-mixed molecular cloud 3-8 Myr after massive star formation. The large black point is the inferred composition of the Solar System. The line represents the Galactic average abundance ratio from γ -ray observations (Wang et al. 2007).