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The plausible source(s) of ^{26}Al in the early solar system: A massive star or the X-wind irradiation scenario?

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Abstract–A quantitative analysis is presented for the irradiation contributions of the short-lived nuclides, specifically ^{26}Al, by the X-wind scenario in the early solar system. The analysis is based on the comprehensive numerical simulations of the scenario that involves thermal processing of protoCAIs during the decades long X-wind cycle. It would be difficult to explain the canonical value of ^{26}Al/^{27}Al in Ca-Al-rich inclusions on the basis of its inferred irradiation yields. Hence, the bulk inventory of ^{26}Al in the early solar system was not produced by the X-wind scenario. We suggest the predominant occurrence of gradual flares compared to impulsive flares in the early solar system as in the case of the modern solar flares. One tenth of the bulk ^{26}Al was only produced by irradiation in case the entire solar inventory of ^{10}Be was produced by local irradiation. The bulk ^{26}Al inventory along with ^{60}Fe was probably synthesized by a massive star. We present a qualitative model of the astrophysical settings for the formation of the solar system on the basis of a survey of the presently active star forming regions. We hypothesize that the formation of the solar system could have occurred almost contemporaneously with the formation of the massive star within a single stellar cluster. As the massive star eventually exploded as supernova Ib/c subsequent to Wolf-Rayet stages, the short-lived nuclides were probably injected into the solar proto-planetary disc. The dynamically evolving stellar cluster eventually dispersed within the initial ~10 million years prior to the major planetary formation episodes.

INTRODUCTION

In order to understand the initial conditions that led to the formation of our solar system around 4.56 billion years ago, it is extremely important to decipher the source(s) of the short-lived nuclides, ^{26}Al ($T_{½}$ ~0.74 Myr; million years), ^{41}Ca (0.1 Myr), ^{36}Cl (0.3 Myr), ^{60}Fe (1.5 Myr), and ^{53}Mn (3.7 Myr), that were present in the early solar system. The origin of these nuclides is still a debated issue. It has been argued that some of these nuclides were either produced by a stellar nucleosynthetic source prior to the formation of the solar system (Boss and Goswami 2006; Meyer and Zinner 2006; Sahijpal and Soni 2006; Wasserburg et al. 2006), or by irradiation during intense magnetic flaring in the early solar system (Shu et al. 1997, 2001; Gounelle et al. 2001, 2006; Leya et al. 2003; Chaussidon and Gounelle 2006; Sahijpal and Soni 2007). The identification of the exact source has become even more challenging subsequent to the recent discovery of ^{10}Be (McKeegan et al. 2000; Chaussidon et al. 2006) with a half life of ~1.36 Myr (Nishiizumi et al. 2007), and the revised estimates of ^{60}Fe/^{56}Fe (Mostefaoui et al. 2005; Tachibana et al. 2006). The presence of high levels of ^{60}Fe necessitate a stellar source, whereas, the presence of ^{10}Be can be explained either by irradiation in the early solar system, or by the galactic cosmic rays trapping scenario recently proposed by Desch et al. (2004). In addition to ^{10}Be, the presence of ^{7}Be in the early solar system has been also suggested recently (Chaussidon et al. 2006). If the widespread presence of ^{7}Be is established, the short-lived nuclide would provide a definite argument in favor of the irradiation production of at least some of the short-lived nuclides in the early solar system. The possibility of intense flaring is also supported by the astronomical observations of young stellar objects (YSOs). The recent X-ray flare observations by the imaging satellites help in characterizing the nature of these superflares (Feigelson et al. 2002; Wolk et al. 2005). As stellar and irradiation sources were both involved in synthesizing the short-lived nuclides, it would be essential to establish their individual contributions, specifically in the case of ^{26}Al. The decay energy of ^{26}Al along with ^{60}Fe could have provided the heat for the differentiation of planetesimals in the early solar system (see e.g., McCoy et al. 2006; Sahijpal et al. 2007).

Among all the proposed irradiation scenarios, the X-wind irradiation scenario deals with the thermal processing of Ca-Al-rich inclusions (CAIs) along with the irradiation production of short-lived nuclides within the magnetic reconnection ring (Shu et al. 1997, 2001). Based on this scenario, a comprehensive numerical code for the thermal processing and irradiation of protoCAIs has been recently developed (Sahijpal and Soni 2007). In these simulations, the X-ray flares are numerically triggered in accordance with the frequency and luminosity of the X-ray flares observed in YSOs (Feigelson et al. 2002; Wolk et al. 2005). The grains introduced into the reconnection ring are irradiated and thermally processed by the flares. Prior to these simulations the irradiation yields of the short-lived nuclides were estimated based on the *assumed* isotopically homogenized ensemble of protoCAIs (Gounelle et al. 2001). It is extremely important to quantitatively investigate this basic assumption regarding the isotopic homogenization of the irradiation yields. It needs to be demonstrated whether the X-wind irradiation scenario can intrinsically reproduce the observed experimental uniform isotopic abundances of the radionuclides by homogenizing the various isotopic inventories produced by irradiation in the magnetic reconnection ring.

The main objective behind developing a comprehensive numerical code for the X-wind irradiation scenario (Sahijpal and Soni 2007) is to infer the spread in the irradiation yields of the short-lived nuclides subsequent to the decades long irradiation of protoCAIs in the magnetic reconnection ring. These yields are compared with the observed abundances of the short-lived nuclides in various meteoritic phases to verify the feasibility of the scenario. Thus, the X-wind irradiation scenario should explain the inherent primary spread in the canonical value of $^{26}Al/^{27}Al$ (MacPherson et al. 1995). In the present work, we have developed a numerical code for the first time to infer the spreads in the irradiation yields of the short-lived nuclides, $^{7,10}Be$, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{53}Mn for an ensemble of protoCAIs that was thermally evolved over a grain-size distribution during the proposed decades long X-wind cycle (Shu et al. 1997). Further, if the entire inventory of ^{26}Al in the early solar system was not exclusively produced by the irradiation scenario we want to estimate its irradiation contribution for a scenario that can at least produce ^{10}Be exclusively by the X-wind scenario. Finally, we propose a novel astrophysical scenario for the formation of the solar system based on the present understanding of the star-forming regions in case a massive star contributed the short-lived nuclides to the early solar system. Based on a comprehensive analysis of all the proposed stellar sources a massive star could have probably synthesized ^{26}Al and ^{60}Fe along with some of the other short-lived nuclides (Sahijpal and Soni 2006).

NUMERICAL SIMULATIONS

The simulations were performed within the framework of various physico-chemical processes proposed by Shu et al. (1997, 2001). Assumptions were made for incorporating the processes that include vaporization, condensation, coagulation and irradiation of protoCAIs with refractory cores and ferro-magnesium mantles as these grains undergo viscous drag by the protosun's coronal plasma during their Keplerian orbit in the magnetic reconnection ring (Sahijpal and Soni 2007). These assumptions are listed in Table 1 along with the associated shortcomings and our comments. The assumptions 1, 2, 4, 5, and 6 mentioned in the Table 1 are inherent to the proposed X-wind irradiation scenario, whereas, the assumptions 7 and 8 were made to simplify the numerical approach adopted in simulating the model. The third assumption refers to the limited X-ray flare observation data of YSOs by the Chandra X-ray satellite that forms the basis of simulating flares in the simulations. It should be mentioned here that we can only partially explore the parametric space due to our computational limitations and the lack of precise knowledge regarding the physico-chemical conditions prevailing in the vicinity of the protosun.

In the previous work, the simulations were performed for the protoCAIs with three fixed refractory core-size distributions, viz., 32 μm–20 mm, 125 μm–16 mm, and 500 μm–13 mm (Sahijpal and Soni 2007). These distributions were dominated by the protoCAIs with the refractory cores of radii, 32 μm, 125 μm and 500 μm, respectively. Dominant refractory core radius within a grain size distribution is designated with D_c. The two core-size distributions with D_c of 125 μm and 500 μm were found to result in a substantial accumulation of protoCAIs in the reconnection ring. This imposed a stringent constraint on the average rock surface density, $\Sigma_r \geq 1.6$ g cm^{-2} for the accumulation of protoCAIs in the magnetic reconnection ring (Sahijpal and Soni 2007). The major shortcoming of this work was the inability to dynamically evolve the protoCAIs refractory core-size distribution over their proposed decades long thermal processing as it was not possible to evolve D_c over time within a single simulation. Hence, the simulations only presented two distinct snap-shot views of the irradiation at two distinct epochs during the decades long X-wind cycle.

We have now developed a numerical code with a dynamically evolving refractory core-size distribution. Within a simulation, at a specific time during the X-wind cycle, the grain size distribution is dominated by a refractory core of radius D_c that condenses subsequent to the superflares with Lx ~ 10^{31-32} erg s^{-1} for Lp/Lx (proton luminosity/X-ray luminosity) ~0.3 (Sahijpal and Soni 2007). It should be noted that these two superflare luminosities result in complete vaporization of core-mantle assemblages within the flare area. Subsequent to the culmination of these flare, the refractory cores re-condense according to the average rock surface density (Σ_r) prevailing in the magnetic reconnection ring (Shu et al. 2001). The theoretical formulation developed by Shu et al. (2001) suggests that the core size of a typical (and dominant) refractory core depends upon the average rock surface density

Table 1. The assumptions used in numerically simulating the X-wind scenario.

	Assumptions	Comments and shortcomings
1	Dipole field approximation of the magnetic field of the protosun (Shu et al. 2007). This results in a planar geometry of the magnetic reconnection ring.	Recent works indicate complex magnetic fields with the existence of higher orders term in the multipole expansion (Gregory et al. 2006, 2007a, 2007b; Jardine et al. 2006; Long et al. 2007, 2008; Donati et al. 2007, 2008; Romanova et al. 2008).
2	Keplerian orbits assumed for the protoCAIs with the coronal plasma viscous drag (Shu et al. 2001). Magnetic field effects on the charged protoCAIs were ignored.	Magnetic effects are difficult to incorporate in simulations. These effects are predominant for grains <100 µm and hence would be of minimum for the present work (Sahijpal and Soni 2007).
3	X-ray flare observations in Lx ~ 10^{29-32} erg s^{-1} of YSOs by the Chandra X-ray satellite (Feigelson et al. 2002; Favata et al. 2005; Wolk et al. 2005) were used to parametrically model the simulation.	Due to the limited data the anticipated flares with Lx ≥ 10^{33} erg s^{-1} cannot be accounted properly. The flares with Lx ≤ 10^{28} erg s^{-1} that could be more predominant in the early solar system are below the detection limit of the Chandra X-ray satellite. These flares cannot be appropriately accounted in the model.
4	The proton luminosities were estimated using Lp/Lx ~ 0.3 (Feigelson et al. 2002).	This is a debatable issue as mentioned earlier (Sahijpal and Soni 2007). Even a factor of three variation will bring in drastic change in the thermodynamical criteria opted for protoCAIs evolution.
5	The ambient temperature attained by protoCAIs and the assumed proton flux during a flare were estimated based on the linear extrapolation of the modern solar flares (Shu et al. 2001).	An alteration in these parameters would significantly influence the thermal evolution of protoCAIs as discussed previously by Sahijpal and Soni (2007). Due to the limited knowledge of the physics of the superflare associated with YSOs it is difficult at present to precisely quantify these parameters.
6	Assumed predominant occurrence of impulsive flares to produce requisite amount of ^{26}Al (Gounelle et al. 2006).	The flare nature is a matter of speculation as far as the X-wind model is concerned. However, the modern solar flares indicate predominant occurrence of gradual flares (Leya et al. 2003).
7	Adopted criteria for the grain condensation and evaporation with an enhanced dust/gas ~50–100 × solar and the total gaseous pressure P_{Total} ~ 10^{-3} atm., or an enhanced dust/gas > 500 × solar and P_{Total} ~ 10^{-6} atm. (Yoneda and Grossman 1995; Ebel and Grossman 2000).	These assumptions were made to facilitate the numerical simulation according to the proposed criteria of the irradiation of ensemble of core-mantle assemblages (Shu et al. 2001). This is again a highly debatable issue due to the lack of the precise knowledge of the pressure-temperature and dust/gas prevailing during flare activities in the reconnection ring. Variations in these parameters would significantly influence the thermal processing of protoCAIs.
8	We adopted a specific criterion for the evaporation of core-mantle assemblages during flares. Corresponding to Lx ~ 10^{32-31} erg s^{-1}, the entire grains were vaporized. Only the mantles were vaporized during Lx ~ 10^{30} erg s^{-1} flares, whereas, the grains were not vaporized during Lx ~ 10^{29} erg s^{-1} flares (Sahijpal and Soni 2007).	This corresponds to the simplest criterion that can be numerically simulated with the various assumptions made above (Sahijpal and Soni 2007). We assumed that the entire inventory of the grains in the reconnection ring acquires the core-mantle configuration with the three discrete set of choices for the thermal processing of core-mantle assemblages corresponding to the four X-ray luminosities, i.e., 10^{29-32} erg s^{-1}. A hierarchal coagulation model was used for coagulation.

(Σ_r). With the increase in Σ_r, the D_c increases. We have now developed a numerical code where we can simulate the increase in D_c with Σ_r during a single X-wind cycle lasting over decades. This approach is based on the theoretical formulation developed by Shu et al. (2001) except for the fact that no observed accumulation of the protoCAIs in the magnetic reconnection ring takes place in our numerical code for D_c <100 µm (Sahijpal and Soni 2007). We proceed with the D_c beyond 100 µm in our present code. In nutshell, we can now simulate the dynamical evolution of the core-size distribution with refractory cores greater than 100 µm. It should be noted that this is not a limitation of our numerical approach but reflects the short residence time of the grains with <100 µm refractory cores in the magnetic reconnection ring that hinders their significant accumulation in the reconnection ring. As mentioned in the Table 1, it should be noted that the choices of the pressure-temperature conditions and the dust to gas ratio prevailing during flares in the magnetic reconnection ring are highly debatable issues that need to be addressed to understand the thermodynamical criteria for grain condensation and evaporation in the magnetic reconnection ring.

The dynamical evolution of the grain size distribution with the increase in the average rock surface density would enable us to understand the temporal evolution of the irradiation yields of the short-lived nuclides over the decades long X-wind cycle. The contributions from the numerous X-wind cycles in turn would finally decide whether the inventories of the short-lived nuclides in the early solar system could be explained by the proposed irradiation scenario.

The ensemble of protoCAIs with the refractory cores in the size range (118 µm–1.06 cm) was thermally evolved over the decades long X-wind cycle. Due to their short residence time (<75 days) in the magnetic reconnection ring, the grains with size <100 µm do not significantly contribute to the net accumulation of grains within the reconnection ring unless these grains are quickly coagulated to form larger grains (Sahijpal and Soni 2007). The newly refined grain size distribution now consists of fourteen refractory cores with the radii ratio of $2^{1/2}$ between two successive core sizes. This is an improvement over an earlier division of the grain size distribution into eight distinct core sizes (Sahijpal and Soni

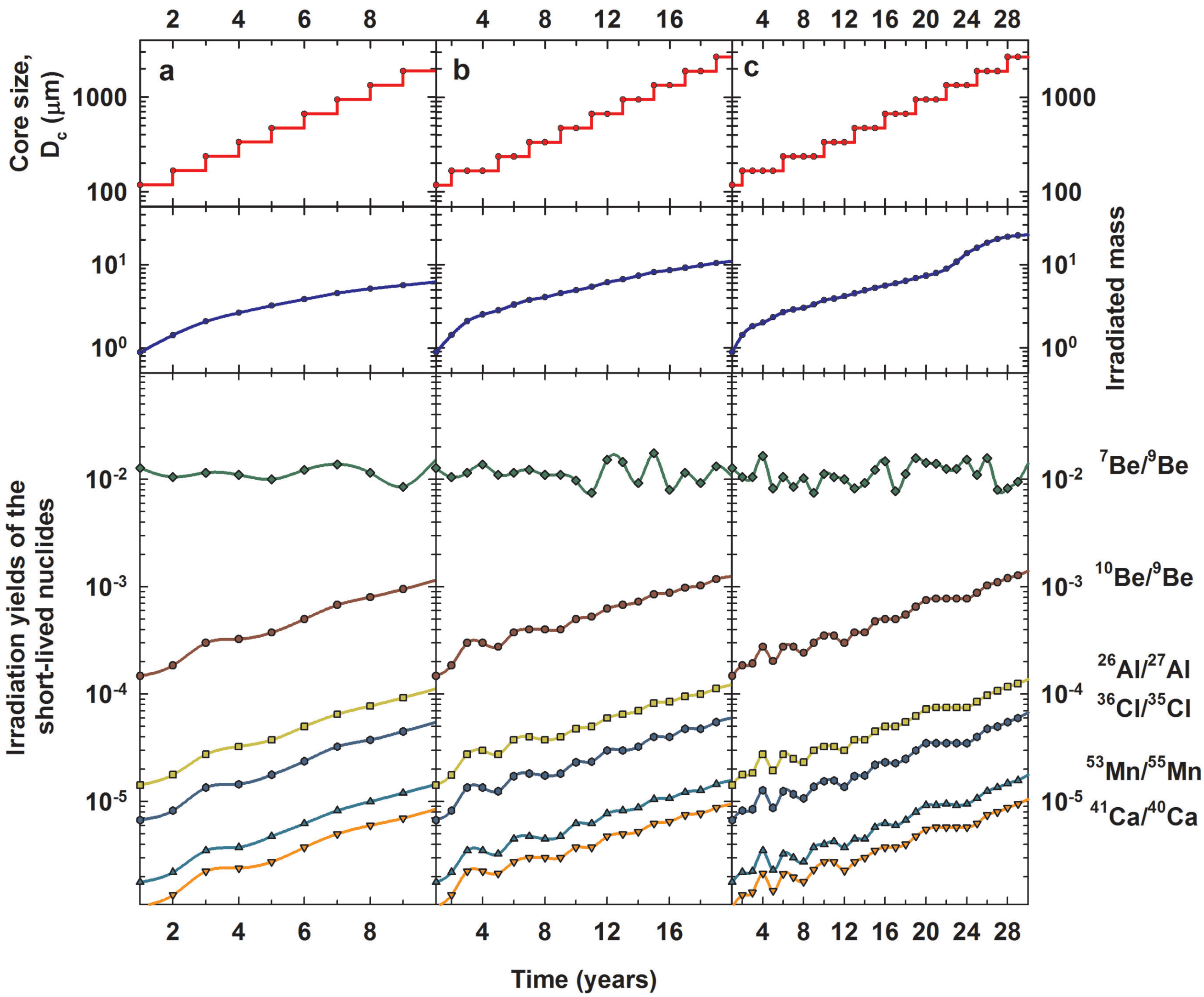

Fig. 1. The bottom panels represent the temporal evolution of the average irradiation yields of the short-lived nuclides over the X-wind cycle corresponding to three distinct evolutionary trends of the core-size distribution over 1–3 decades. The top panels represent the assumed stepwise increase in the dominant refractory core size (D_c) over the X-wind cycle, with the middle panels representing the normalized increase in the irradiated protoCAIs mass in the reconnection ring. Impulsive flares were triggered in the simulations with ^{3}He/proton = 0.3, ^{4}He/proton = 0.1, Lp/Lx (proton luminosity/X-ray luminosity) = 0.3, and the energy spectra, $dN/dE \propto E^{-4}$ (Sahijpal and Soni 2007).

2007). The simulations were initiated with D_c = 118 μm as the dominant refractory core that condense subsequent to the superflares with Lx ~ 10^{31-32} erg s^{-1} for Lp/Lx ~ 0.3 (Sahijpal and Soni 2007). We considered three distinct evolutionary trends in the increase of the dominant refractory core size (D_c) with time within a single X-wind cycle lasting over 1–3 decades. The dominant refractory core size was increased in a stepwise manner from 118 μm to ~2 mm. The three representative set of simulations are presented in Figs. 1a–c. These set of simulations could help in deducing the dependence of the irradiation yields of the short-lived nuclides not only on the evolutionary trend of the core-size distribution but also on the time-span of a single X-wind cycle.

Several additional refinements have been made in the present numerical code at a computational level although the basic criteria adopted for the physico-chemical processes remain almost the same as used by Sahijpal and Soni (2007). The 0.25 R_x wide reconnection ring has been now divided into twenty concentric annular zones compared to the previous division into five concentric zones (Sahijpal and Soni 2007). The reduction in the discreteness in the division of the reconnection ring would be helpful in reducing any excessive amount of mixing of the inventories of the short-lived nuclides during a specific flare. In the previous numerical code, the 0.05 R_x wide annular zone of the reconnection ring was isotopically homogenized during a flare against the present 0.0125 R_x wide annular zone. A single typical flare

Table 2. Final average yields of the short-lived nuclides for a wide range of parameters for the numerically triggered flares.

	^{10}Be/^{9}Be	^{41}Ca/^{40}Ca	^{26}Al/^{27}Al	^{7}Be/^{9}Be	^{53}Mn/^{55}Mn	^{36}Cl/^{35}Cl	
		Reference	Initial	Values			
	$(4–9) \times 10^{-4}$	1×10^{-8}	5×10^{-5}	6×10^{-3}	2×10^{-5}	$(4–10) \times 10^{-6}$	Nature of the flares
1	5.0×10^{-4}	8.3×10^{-9}	5.3×10^{-7}	4.8×10^{-4}	8.8×10^{-6}	1.8×10^{-7}	Grad. ($\gamma = 3$)
2	5.5×10^{-4}	6.0×10^{-7}	8.5×10^{-6}	1.2×10^{-3}	9.3×10^{-6}	4.0×10^{-6}	Grad. ($\gamma = 3$) and Imp. ($\gamma = 4$) occurrence ratio = 9:1
3	8.8×10^{-4}	4.8×10^{-6}	6.3×10^{-5}	1.7×10^{-2}	1.2×10^{-5}	3.0×10^{-5}	Grad. ($\gamma = 3$) and Imp. ($\gamma = 4$) occurrence ratio = 1:1
4	1.2×10^{-3}	3.0×10^{-6}	4.0×10^{-5}	5.8×10^{-3}	1.5×10^{-5}	2.2×10^{-5}	Imp. ($\gamma = 4$)
5	1.2×10^{-3}	8.5×10^{-6}	1.1×10^{-4}	1.5×10^{-2}	1.5×10^{-5}	5.5×10^{-5}	Imp. ($\gamma = 4$)
6	1.4×10^{-3}	6.0×10^{-6}	7.5×10^{-5}	1.3×10^{-2}	1.3×10^{-5}	3.8×10^{-5}	Imp. ($\gamma = 3$ & 4)

Yields were calculated for one decade of irradiation with the evolutionary trend in the grain size distribution corresponding to Fig. 1a simulation.
^{4}He/proton = 0.01 for the gradual (Grad.) flares.
^{3}He/proton = 0.3 (except for 0.1 for the simulation #4) and ^{4}He/proton = 0.1 for the impulsive (Imp.) flares.
Lp/Lx = 0.3, and the energy spectra, $dN/dE \propto E^{-\gamma}$, was used (Sahijpal and Soni 2007).

with Lx ~ $10^{30–31}$ erg s^{-1} that lasts for a few hours can only locally homogenize the inventories of the short-lived nuclides produced by irradiation. Hence, the present choice for the division of the reconnection ring would be better than the one adopted earlier. In totality, the resolution of the simulation has been increased by a factor of seven, thereby increasing the reliability by reducing the discreteness in the division of the reconnection ring and the refractory core sizes. The presently adopted grain size distribution with fourteen refractory core sizes against the previously used eight refractory core sizes can be treated as almost a continuum of the core sizes rather than a discrete set. Additional nuclear reactions have been included for the production of ^{36}Cl and ^{7}Be. These include ^{35}Cl(^{3}He,x)^{36}Cl, ^{34}S(^{3}He,x)^{36}Cl, ^{39}K(^{3}He,x)^{36}Cl and ^{16}O(^{3}He,x)^{7}Be (Gounelle et al. 2006) reaction cross sections.

RESULTS

The results obtained from a representative set of simulations with the three assumed trends in the evolution of protoCAIs core size distribution are presented in Fig. 1 and Table 2. The average irradiation yields of the short-lived nuclides, except ^{7}Be ($T_{1/2}$ ~53 days), gradually increase over time with the evolution of the core-size distribution (Fig. 1). This is inherently expected for the irradiation of an evolving ensemble of protoCAIs over an X-wind cycle lasting over decades due to the accumulation of protoCAIs in the reconnection ring. This aspect has never been appropriately considered in the original proposed scenario (Shu et al. 1997, 2001). Further, the three distinct choices of the evolution of the core-size distribution infer distinct yields of the short-lived nuclides even for an identical X-wind irradiation time-span. These findings could impose stringent constraints on the contribution of the short-lived nuclides by the irradiation scenario. However, due to the lack of the precise knowledge of the physico-chemical processes operative in the vicinity of the protosun and our computational limitations we cannot at present generalize our findings. The generalization could only be achieved by considering the multitude of possibilities in the pressure-temperature conditions along with the dust to gas ratio prevailing during the condensation and vaporization of protoCAIs.

The inferred irradiation spreads in the ^{26}Al/^{27}Al ratio at different epochs during a decade(s) long X-wind irradiation cycle are presented in Fig. 2. The spreads corresponding to the maxima in the yields are marked in the figure by horizontal bars, and are designated as $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_{\mathrm{maxima}}$. The canonical value of ~5×10^{-5} for ^{26}Al/^{27}Al is indicated by the thick vertical line dropped from the top of each panel in the figure. Even in the case of a single X-wind cycle it would be difficult to eventually produce the observed spread in the canonical value of ^{26}Al/^{27}Al (Fig. 2) after decades of irradiation. Further, it would be even more difficult to produce the well defined canonical value that is represented by the thick vertical line.

DISCUSSION

Detailed numerical simulations have been performed for the thermal processing and irradiation of protoCAIs within the X-wind irradiation formulation. The protoCAIs grain size distribution was evolved over decades long X-wind cycle to study the irradiation contribution of the short-lived nuclides, ^{7,10}Be, ^{41}Ca, ^{36}Cl, ^{53}Mn, and ^{26}Al to the early solar system. One of the prime objectives of the present work was to quantitatively analysis the X-wind irradiation scenario to figure out whether ^{26}Al can be exclusively produced by the scenario. This goal was achieved by comparing the final irradiation yields of ^{26}Al/^{27}Al with its observed experimental values.

X-Wind Scenario and the Canonical Value of ^{26}Al/^{27}Al

The numerical simulations of the thermal processing and irradiation of a dynamically evolving grain size distribution of protoCAIs infer a wide spread in the irradiation yields of

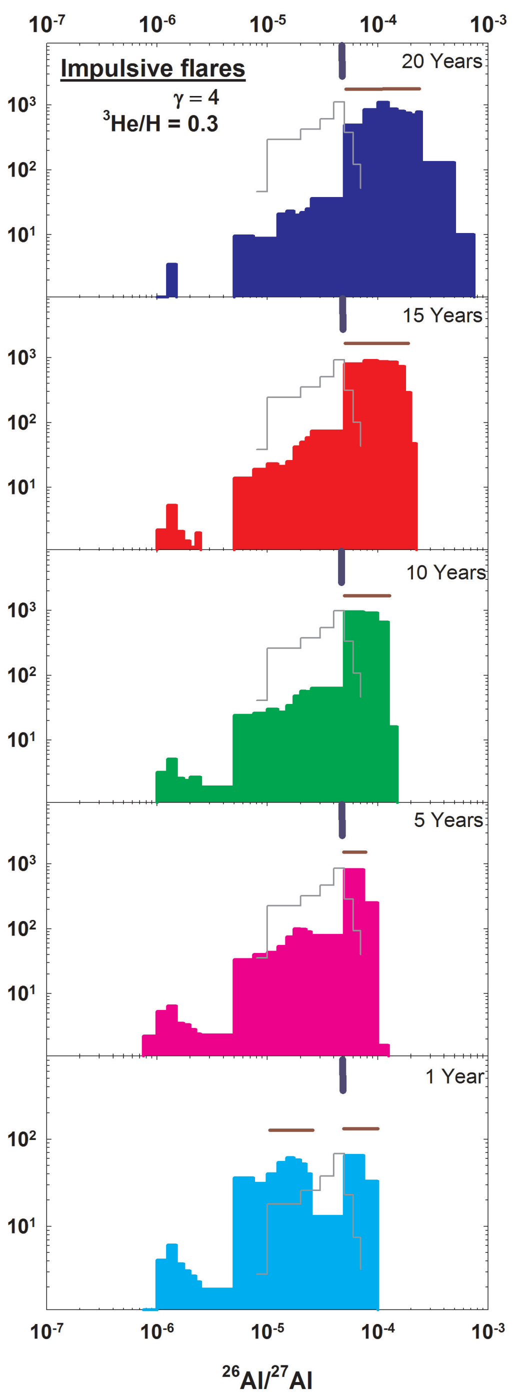

Fig. 2. Time evolution of the renormalized differential spectra of the irradiation yields of $^{26}Al/^{27}Al$ during a single X-wind irradiation cycle corresponding to the simulation results presented in Fig. 1b. The thick vertical line dropped from the top of each panel represents the well defined canonical value of $^{26}Al/^{27}Al$ (MacPherson et al. 1995). The renormalized observed experimental spread around the canonical value (MacPherson et al. 1995) is presented in all the panels. The thick horizontal lines represent the inferred spread in the $(^{26}Al/^{27}Al)_{maxima}$ values. Decades of irradiation result in the spread that is significantly larger than even the observed spread around the canonical value of $^{26}Al/^{27}Al$. It would be even more difficult to produce a well defined canonical value.

$^{26}Al/^{27}Al$ (Fig. 2). The renormalized observed experimental spread (MacPherson et al. 1995) around the canonical value is graphically presented in Fig. 2. The majority of the observed experimental spread around the canonical value of ~5×10^{-5} for $^{26}Al/^{27}Al$ in the case of normal Ca-Al-rich inclusions (MacPherson et al. 1995) is in the range of $(3–5) \times 10^{-5}$. More than two-third of the experimental values fall within this range. However, it should be noted that in majority of the Ca-Al-rich inclusions with $^{26}Al/^{27}Al$ ratio distinct from the canonical value of ~5×10^{-5}, the variations are generally attributed either to secondary alterations in CAIs or analytical uncertainties in the pre-1995 data mostly obtained by SIMS (secondary ion mass spectrometry) (MacPherson et al. 1995). The observed experimental spread cannot be considered at its face value to be the representative of the primary inherent nebular spread. In well documented CAIs there is a correlation between the disturbed Al-Mg isotopic systematic and the presence of secondary altered minerals (see e.g., Podosek et al. 1991; MacPherson and Davis 1993; Caillet et al. 1993; Fagan et al. 2006; MacPherson et al. 2007). However, in the case of CM hibonites with the stable isotopic anomalies in calcium and titanium, the absence of ^{26}Al, or extremely low $^{26}Al/^{27}Al$ ratios is generally considered to be either due to spatial or temporal heterogeneity (e.g., Podosek et al. 1991; MacPherson et al. 1995; Sahijpal and Goswami 1998; Sahijpal and Soni 2006). Further, in the case of CAIs from CV chondrites, the analytical uncertainties in the pre-1995 data, specifically for the phases with Al/Mg ratio less than 100, e.g., hibonite and melilite, could be considered as the major cause of the broad spread in $^{26}Al/^{27}Al$ (Dr. G. J. MacPherson; personal communication). The influence of analytical uncertainties is well marked in type A CAIs that exhibit a broader spread compared to type B CAIs in spite of the fact that the former are less processed by secondary alterations (see Fig. 5 of MacPherson et al. 1995). The recent date obtained on CV CAIs phases with low Al/Mg ratios by MC SIMS (multi-collector secondary ion mass spectrometer) (Jacobsen et al. 2008b) exhibit more scatter than the data obtained by MC-ICP-MS (multi-collector inductive-coupled-plasma mass spectrometer). This could be partially attributed to both analytical uncertainties in SIMS data along with the disturbances on small spatial scale in the analyzed phases (Dr. B. Jacobsen; personal communication).

The recent refinements in the analytical techniques (Bizzarro et al. 2004; Jacobsen et al. 2007a, 2007b, 2008a, 2008b; Yin et al. 2008) indicate a well defined "canonical value" of ~5×10^{-5} for $^{26}Al/^{27}Al$ in the early solar system. The detailed petrographic studies and the high precision Al-Mg isotopic data on CAIs obtained by MC-ICP-MS suggest that the exact inherent spread around the canonical value of $^{26}Al/^{27}Al$ was extremely small. Recent results obtained by Baker (2008) and Bouvier et al. (2008) further support a well defined canonical value of ~5×10^{-5} for $^{26}Al/^{27}Al$. Numerous studies have also indicated the role of ^{26}Al as a high resolution chronometer to date nebular events spread over a few tens of kyr (Thrane et al. 2006; Jacobsen et al. 2008a, 2008b; Yin et al. 2008). Even though, there have been some claims of the supra-canonical values $>5 \times 10^{-5}$ for ^{26}Al/^{27}Al but such claims have been recently challenged by the high precision data obtained by MC-ICP-MS (Jacobsen et al. 2007a, 2007b, 2008a, 2008b; Yin et al. 2008). Nonetheless, these inclusions are scanty in number and would not modify even the renormalized observed experimental spread in ^{26}Al/^{27}Al ratio. The various arguments associated with the analytical uncertainties and the secondary alterations in CAIs indicate that the observed spread in the ^{26}Al/^{27}Al ratio probably evolved from a well defined canonical value of 5×10^{-5}. The primary inherent nebula spread was probably extremely narrow.

The inferred irradiation spread of more than a factor of two in the $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_{\mathrm{maxima}}$ ratio subsequent to a decade(s) long X-wind cycle cannot explain the canonical value of $\sim 5 \times 10^{-5}$ for ^{26}Al/^{27}Al (Fig. 2). Hence, the irradiation production of ^{26}Al subsequent to the proposed decade(s) long irradiation (Shu et al. 2001) by the X-wind cycle seems to be unlikely. However, subsequent to the initial five years the inferred irradiation spread in the $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_{\mathrm{maxima}}$ ratio is around a factor of ~1.5 (Fig. 2). This is comparatively lower than the spread inferred for the other irradiation time-spans. However, as discussed above, the inherent primary nebula spread in the ^{26}Al/^{27}Al around the canonical value could be extremely small (e.g., Thrane et al. 2006; Jacobsen et al. 2007a, 2007b, 2008a, 2008b). Even the short irradiation timescale of five years produces spread that is still too large to explain a well defined canonical value. Secondly, the irradiation time-span of five years is significantly shorter than the formulated decades long X-wind irradiation cycle that involves physico-chemical processing of protoCAIs (Shu et al. 2001). Further, it should be noted that in order to produce the bulk inventory of ^{26}Al in the solar nebula numerous decades long X-wind cycles would be required. Each of this X-wind cycle has to independently produce a well defined canonical value. Within the viable variances of the numerous physico-chemical processes and the time-spans of X-wind cycles (Shu et al. 1997) it would be difficult to eventually obtain the well defined canonical value of ^{26}Al/^{27}Al with the repeated X-wind cycles. In order to reproduce the canonical value of ^{26}Al/^{27}Al in the early solar system either the irradiation yields of the numerous X-wind cycles were thoroughly homogenized, or the bulk ^{26}Al inventory of the early solar system was probably of stellar origin (Boss 2008).

Within the X-wind irradiation formulation we can envisage two hypothetical scenarios for the homogenization of the irradiation yields of the short-lived nuclides subsequent to the thermal evolution of protoCAIs. Both of these scenarios would require complete vaporization of the irradiated protoCAIs, followed by isotopic homogenization and re-condensation of protoCAIs and/or CAIs. These scenarios include isotopic homogenization within 1) the magnetic reconnection ring by superflare(s), 2) the highly turbulent nebula by transient heating episodes.

The former scenario would involve homogenization of the irradiation yields of protoCAIs by superflares with X-ray luminosities, Lx ~ 10^{34} erg s^{-1}. These superflares would be required to vaporize the protoCAIs over the entire magnetic reconnection ring area and cause widespread isotopic homogenization (Shu et al. 2001; Sahijpal and Soni 2007). The homogenization would be subjected to the stringent assumption of mixing the isotopic inventories spread over the entire magnetic reconnection ring during the timescale of the flare that could last for a day or less. In case these superflares were prevalent in the early solar system, their frequent occurrence could have produced a well defined ratio of ^{26}Al/^{27}Al, at least distinctly for different X-wind cycles. However, these superflares have not been reliably observed to date (Feigelson et al. 2002; Skinner et al. 2003; Grosso et al. 2004; Favata et al. 2005; Wolk et al. 2005). Nonetheless, it should be mentioned that the entire X-ray coverage of the Orion protostars is equivalent to observing one protostar for merely ~50 years. Based on the confirmed observational evidence of the flares with Lx ~ 10^{32} erg s^{-1}, the predominant flares with Lx ~$10^{30\text{-}31}$ erg s^{-1}, and the anticipated power law distribution of the flare energies (Wolk et al. 2005), we can hypothesize the frequency of the superflares with Lx ~10^{33-34} erg s^{-1}. At a frequency of ~33 flares with Lx ~10^{32} erg s^{-1} in 5 years (Sahijpal and Soni 2007) there would be ~1 superflare with Lx ~10^{33} erg s^{-1} in every two decades, and ~1 superflare with Lx ~10^{34} erg s^{-1} every 10^3 years. There would be a total of 10^3 superflares with Lx ~10^{34} erg s^{-1} in the initial one million year of the solar system. Since the estimated number of these superflares is extremely small it is unlikely that these flares occurred periodically and accurately at the end of every single decades long X-wind cycle to homogenize the irradiation yields of the short-lived nuclides. Hence, the essential requirement of the superflares with Lx ~10^{34} erg s^{-1} to homogenize the entire isotopic inventories of the magnetic reconnection ring cannot be satisfied for each decades long X-wind cycle. Even if these superflares were occurring in the early solar system, these flares could have themselves produced the short-lived nuclides by irradiation of the completely vaporized reservoirs of nebula dust (Sahijpal and Soni 2007) without any contributions from the X-wind irradiation. The X-wind irradiation scenario would not be required at all in case the superflares with Lx ~10^{34} erg s^{-1} is essential for the scenario to work.

The alternative scenario would involve thermal reprocessing of the irradiated protoCAIs by transient heating episodes within a highly turbulent solar nebula. In this scenario, subsequent to their irradiation within the magnetic reconnection ring, the protoCAIs would be launched at varied distances in the solar nebula by the X-winds. In a highly turbulent nebula there is a possibility that these protoCAIs would be thermally reprocessed and isotopically homogenized by transient heating events to produce the canonical value of the short-lived nuclide in the nebula. It should be noted that this scenario is distinct from the original scenario proposed by Shu et al. (1997) to explain the final stage thermal reprocessing of protoCAIs. In this scenario, the transient heating episodes in the highly turbulent solar nebula would be essential to homogenize the irradiation yields of the short-lived nuclides and produce the Ca-Al-rich inclusions in the nebula rather than at the X-point. This scenario would be identical to the chondrule formation scenario recently proposed by Miura and Nakamoto (2007).

Finally, in order to consider any contribution(s) of the short-lived nuclides from the irradiation scenario several additional issues have to be resolved. The various assumptions (Table 1) made for the physico-chemical processes involved in the irradiation scenario (Shu et al. 1997) and those required to numerically simplify the problem have to be thoroughly investigated. These aspects were discussed in detail elsewhere (Sahijpal and Soni 2007).

In case the observed yields of ^{10}Be were exclusively produced by the X-winds irradiation scenario, we anticipate a minimum of ~10% irradiation contribution to the initial ^{26}Al (Table 2). This inference is based on the simulations where the gradual flares dominated the early solar system as in the case of modern sun (Leya et al. 2003). The remaining solar system inventory of ^{26}Al was probably of stellar origin. The comprehensive analyses of the various plausible stellar sources suggest that a massive star could have contributed ^{26}Al and ^{60}Fe to the early solar system (Sahijpal and Soni 2006). This scenario would involve injection of short-lived nuclides either into the presolar cloud or proto-planetary disc. In contrast to the original proposed X-wind irradiation scenario, the stellar scenario would inherently produce a canonical value of ^{26}Al/^{27}Al on account of rapid mixing of the stellar ejecta into the solar nebula (e.g., Sahijpal and Soni 2006). The astrophysical settings for the formation of the solar system and the massive star needs to be understood and is presently explored.

Astrophysical Settings for the Formation of the Solar System

Stars are generally formed in embedded stellar clusters (Lada and Lada 2003; Hester et al. 2004; Ouellette et al. 2005, 2007; Weidner and Kroupa 2006; Kroupa 2008). Whether a cluster of low-mass stars, e.g., the Taurus-Auriga complex, or an OB association, e.g., the Trapezium cluster, is formed generally depends upon the cluster mass (Weidner and Kroupa 2006). The possibility that the massive star and the solar system were formed >10 parsecs apart seems to be low (Cameron et al. 1995; Cameron 2003; Sahijpal and Soni 2006). The proposed triggered star formation in the Scorpius cluster by the shock waves from the supernova in Centaurus, ~75 parsecs away (Preibisch and Zinnecker 2007) cannot be used as an analogy for the supernova triggered formation of the solar system in case ^{26}Al was exclusively produced by the supernova. Sahijpal and Soni (2006) have recently performed detailed analyses of the stellar contribution of ^{26}Al with various isotopic and dynamical constraints. In order to produce the canonical value of ^{26}Al/^{27}Al in the early solar system along with the triggered formation of the solar system, the massive star should probably reside within a couple of parsecs from the presolar cloud of radial dimensions <0.1 parsec (Sahijpal and Soni 2006). The most massive star with the maximum ^{26}Al yield of 2.7×10^{-4} $M_\odot$ (see Table 1 of Sahijpal and Soni 2006) and an injection efficiency of 10% in the presolar cloud of radius ~0.1 parsec (Vanhala and Boss 2000), subsequent to one free decay time interval would produce the canonical value of ^{26}Al/^{27}Al in the early solar system provided it is at a distance of ~3.5 parsecs. This limit can be relaxed to ~10 parsecs either in the case that the injection efficiency is raised to 100% or the radial dimensions of the presolar cloud is increased by a factor of three thereby reducing its density. These departures from the assumed set of parameters used in the numerical simulations by Vanhala and Boss (2000) would require a fresh feasibility analysis of the conditions necessary to trigger star formation (Foster and Boss 1996). In general, the massive star that contributed ^{26}Al could have been quite close, probably a couple of parsecs to the presolar cloud (Sahijpal and Soni 2006). Hence, the massive star and the presolar cloud should either belong to the same stellar cluster as in the case of the stars within the Orion molecular cloud or the Upper Scorpius complex, or at least the two were related with two extremely close clusters.

The probability of a supernova (SN) triggering star formation over shorter distances of a few parsecs would be less than that of a SN injecting short-lived nuclides into an already existing proto-planetary disc as the former could probably lead to the disruption of the presolar cloud. There is no observational evidence to support triggered star formation by supernova at short distances of a few parsecs. On the contrary, the Carina nebula presents numerous environments where the molecular clouds over such short distances have been actually disrupted by the intense winds from the massive stars. Nonetheless, the Carina nebula (Smith 2006; Smith and Brooks 2007) hosts a wide range of triggered star formation environments at comparatively large distances. The star formation in the huge nebula is presently triggered by the ionization fronts and the stellar winds of the numerous massive stars. Ouellete et al. (2005, 2007) proposed a hypothesis for the triggered formation of the solar system by the ionization fronts and stellar winds of a massive star. In this hypothesis, the short-lived nuclides were injected by the supernova explosion of the massive star into the proto-planetary disc. The injection of short-lived nuclides into the proto-planetary disc requires high injection efficiency of dust grains, the carrier of the short-lived nuclides, into the disc.

Some of the earlier studies have figured out an inefficiency of this process (Margolis et al. 1979), while the recent numerical simulations indicate ~100% efficiency (Ouellete et al. 2007).

Apart from the proposed hypothesis of the triggered formation of the solar system by the ionizing fronts and winds associated with the massive star (Ouellette et al. 2005, 2007), an alternative hypothesis could be feasible and needs to be explored. There need not be any sequential relationship between the formation of the massive star and the solar system within the same cluster. It is quite likely that within a cluster the formation of low-mass stars occur spontaneously as a result of local density fluctuations in the self gravitationally contracting pre-cluster cores (Weidner and Kroupa 2006). Subsequently, the massive stars are formed at the cluster core by either rapid accretion scenario or stellar mergers during the embedded dense phase (Bally and Zinnecker 2005; Weidner and Kroupa 2006; Krumholz and Bonnell 2007). Detailed numerical simulations suggest that the low-mass stars are probably formed through the fragmentation of dense filaments and disks in a parent molecular cloud, whereas, the massive stars require continuous accretion in a clustered environment (Bonnell et al. 2007; Larson 2007). The ionizing fronts and the winds of the newly formed massive stars terminate the local star formation (Weidner and Kroupa 2006). This scenario explains the empirical relationship between the mass of the most massive star ($M_{max.}$) within a cluster and the estimated cluster mass by forming stars in an ordered fashion, initiating with the low-mass stars (Weidner and Kroupa 2006). An empirical support to the argument is provided by the recent observation of a stellar cluster where the inferred ages of the pre-main-sequence stars are significantly older than the central OB stars within a single embedded cluster (Feigelson and Townsley 2008). Thus, the initiation of the formation of the solar system could have occurred contemporaneously with the formation of the massive star. The massive star would eventually evolve, undergo core collapse supernova (SN) and inject short-lived nuclides into the proto-planetary disc.

The Massive Star That Could Have Contributed ^{26}Al and ^{60}Fe

As the most massive star within a stellar cluster would be the earliest to evolve, explode and inject short-lived nuclides into the proto-planetary disc, it is essential to infer its mass ($M_{max.}$) and nature. The mass of the stellar cluster would probably determine $M_{max.}$ (Weidner and Kroupa 2006). A single massive star (M_{ZAMS} >30 $M_{\odot}$; solar metallicity), or a primary massive star (M_{ZAMS} >15 $M_{\odot}$; solar metallicity) within a close interacting binary system go through Wolf-Rayet (WR) stage followed by SNIb/c (Woosley et al. 2002; Chieffi and Limongi 2006; Sahijpal and Soni 2006). The massive star could be a potential source of the short-lived nuclides (Sahijpal and Soni 2006). For example, the most massive stellar system in the Trapazium cluster, the θ^1 Orionis C is a close interacting binary with estimated stellar masses of ~34 and ~15 $M_{\odot}$ (Kraus et al. 2007). The massive star of this binary system would probably go through WR+SNIb/c stages. Apart from this scenario, in general, a single massive star >40 $M_{\odot}$ explodes within an interval of 3–5 Myr after its formation compared to ≥7 Myr required by the ≤25 $M_{\odot}$ single stars to explode as SNII. In the case of the injection of short-lived nuclides into the proto-planetary disc, the injection should occur early prior to the significant evolution of the disc, hence the massive star (>40 $M_{\odot}$) would be favorable for the injection of short-lived nuclides.

Around 70% of the O-type stars in the galaxy are generally associated with stellar cluster and/or OB association (Gies 1987). The origin of approximately 4% of the O-type stars cannot be traced to any cluster and association, and hence are the true O-type field stars (De Wit et al. 2004, 2005). While the remaining O-type stars could be categorized as runaway stars. The probability of the survival of a massive star against its dynamical ejection from the cluster as a runaway star (Kroupa 2004; Dray et al. 2005; Pflamm-Altenburg and Kroupa 2006) prior to supernova (SN) could be a major concern for the star to be the source of short-lived nuclides. In this regard, the Upper Scorpius OB association probably represents a suitable case to study an evolved stellar cluster with an age of ~5 million years and a spatial spread of ~25 pc (Preibisch and Zinnecker 2007). The progenitor of the identified pulsar in the cluster, with an estimated mass of 40–60 $M_{\odot}$ (Pflamm-Altenburg and Kroupa 2006) could have injected short-lived nuclides during WR+SNIb/c stages into the proto-planetary discs of the Upper Scorpius cluster stars within a short period of ~3.5 Myr after its formation. This scenario could be a more realistic analog for the formation of the solar system. The injection of ^{26}Al into the proto-planetary disc would also explain the absence of this nuclide in the earliest refractory phases that condensed prior to the injection of the short-lived nuclide (Sahijpal and Goswami 1998).

Finally, in order to avert perturbations to the evolving planetary system in the early solar system it would be essential to avoid close encounters with the companion cluster stars (Malmberg et al. 2007). The stellar cluster should disperse prior to the major planetary formation episode, perhaps within the initial ~10 million years. Otherwise the planets would form with highly eccentric orbits.

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