

Numerical simulations of the production of extinct short-lived nuclides by magnetic flaring in the early solar system

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Abstract—Using the X-ray flare observations of low-mass protostars, we developed numerical simulations of thermal processing and irradiation of protoCAIs in the magnetic reconnection ring within the X-wind formulation. Observed X-ray flare luminosities have been used to model various simulation flare characteristics. Several approximations have been made regarding the thermal evolution that involve condensation, evaporation, and coagulation of protoCAIs. Ensembles of refractory cores with ferromagnesian mantles were evolved for irradiation production of the short-lived nuclides ^7Be , ^{10}Be , ^{41}Ca , ^{36}Cl , ^{26}Al , and ^{53}Mn . Three distinct grain-size distributions of protoCAIs with refractory cores in the ranges of 32 μm –20 mm, 125 μm –16 mm, and 500 μm –13 mm were thermally evolved for irradiation. The latter two size distributions were found to result in the accumulation of protoCAIs in the reconnection ring during an X-wind cycle, and hence can account for the total inventory of ^{26}Al in the early solar system. The canonical value of $\sim 5 \times 10^{-5}$ for $^{26}\text{Al}/^{27}\text{Al}$ can be inferred from the impulsive flare simulations by a suitable choice of simulation parameters. However, in most of the remaining simulations, the irradiation of protoCAIs by superflare(s) with $L_x > 10^{32} \text{ ergs s}^{-1}$ subsequent to their thermal processing in the reconnection ring would be required to explain the experimental abundances of the short-lived nuclides. These superflares have never been reliably observed in young stellar objects. If they are real, they would be extremely rare. The paucity of these superflares could impose stringent constraints on the validity of the X-wind irradiation scenario as the source of the short-lived nuclides.

INTRODUCTION

The presence of the short-lived nuclides in the early solar system, especially those having mean lives $\leq 5 \text{ Ma}$, e.g., ^{26}Al , ^{53}Mn , and ^{41}Ca , has been extensively used in cosmochemistry to decipher various early solar system processes (Podosek and Nichols 1997; Lugmair and Shukolyukov 1998; Birck et al. 1999; Goswami and Vanhalla 2000; Gounelle and Russell 2005). These processes range from the condensation of Ca-Al-rich inclusions (CAIs) to the formation of chondrules, and the formation and subsequent thermal evolution of meteorite parent bodies. The short-lived nuclides, e.g., ^{182}Hf , are also used to deduce differentiation sequences of the terrestrial planets. To understand the cosmochemical implications of the short-lived nuclides, it is essential to decipher their most plausible source(s). A stellar nucleosynthetic origin for most of these could imply their fresh production by an evolved star just prior to the formation of the solar system. This scenario imposes stringent

constraints on the time scales associated with the formation and early evolution of the solar system (Cameron et al. 1995, 1997; Sahijpal et al. 1998; Goswami and Vanhalla 2000). Alternatively, the “local” production by irradiation of nebula gas and dust by energetic particles from magnetic flaring in the early solar system could drastically delimit the cosmochemical implications of some of the short-lived nuclides.

Prior to the discovery of “live” ^{10}Be in the early solar system (McKeegan et al. 2000; Sugiura et al. 2001; MacPherson et al. 2003), stellar nucleosynthesis was considered the most plausible source of the short-lived nuclides. The presence of ^{10}Be , along with the recent evidence for the presence of “live” ^7Be in the early solar system (Chaussidon et al. 2004, 2006), likely illustrate the role played by a local irradiation scenario in the production of at least some of the short-lived nuclides. While ^{10}Be can be produced both by irradiation in the early solar system (Gounelle et al. 2001, 2006; Leya et al. 2003) and by galactic

cosmic rays prior to the formation of the solar system (Desch et al. 2004), the presence of “live” ^7Be favors intense flaring in the early solar system. Even though the widespread presence of ^7Be in the early solar system has yet to be established, the short-lived nuclei could impose temporal, and hence dynamical, constraints on irradiation scenarios.

In contrast to the foreseeable role played by local irradiation in producing certain short-lived nuclides, the recently revised estimates of ^{60}Fe in the early solar system necessitate stellar nucleosynthetic contribution to the presolar cloud (Mostefaoui et al. 2004, 2005; Tachibana and Huss 2003; Tachibana et al. 2006). The eventual goal is to now infer the contributions of stellar nucleosynthesis and local irradiation to the early solar system inventories of ^{41}Ca , ^{36}Cl , ^{26}Al , and ^{53}Mn .

Meteoritic and Astronomical Evidence for Irradiation in the Early Solar System

Apart from the presence of short-lived nuclides, e.g., ^7Be and ^{10}Be , in the early solar system, the irradiation records of magnetic flaring in the early solar system have been found in meteorites as solar flare VH (very heavy, mostly Fe group) ion tracks in the mineral grains from the gas-rich carbonaceous chondrites (Hohenberg et al. 1990; Caffee et al. 1991). These grains were also found to have an excess of spallogenic ^{21}Ne that could not be explained by galactic cosmic ray (GCR) irradiation. The presence of ion tracks and spallogenic ^{21}Ne in these grains necessitate irradiation prior to their compaction in meteorite parent bodies. Magnetic flaring has also been proposed as being responsible for the thermal evolution of CAIs and chondrules (Shu et al. 1996, 1997; Levy and Araki 1989). Finally, the astronomical observations of young stellar objects (YSOs) in X-ray, radio, and optical wavebands indicate intense flaring (Feigelson and Montmerle 1999). It is quite plausible that during its formation, the solar system might have gone through episodes of intense flaring.

Among the various observational wavebands used in the characterization of flaring associated with YSOs, X-ray observations by imaging satellites have been most crucial (Grosso et al. 1997, 2004; Feigelson and Montmerle 1999; Garmire et al. 2000; Feigelson et al. 2002a, 2002b, 2003; Favata et al. 2005; Wolk et al. 2005). YSOs are associated with bipolar outflows that result from the interaction of circumstellar disc with protostellar magnetosphere (Reipurth and Bally 2001). Magnetic flaring in this complex environment could be associated with the interaction of protostellar magnetosphere with the circumstellar disc (Hayashi et al. 1996; Shu et al. 1996; Birk et al. 2000; Isobe et al. 2003). The recent improvements in the spatial resolution of X-ray images achieved by the Chandra X-ray satellite (Garmire et al. 2000) have made it possible to study the temporal evolution of >1000 YSOs in active star-forming

regions, e.g., the Orion nebula cluster (ONC), within a single field of view for a time span of days. These observations have resulted in considerable improvements in the statistics of YSOs flare characteristics. Based on these X-ray flare observations, it is now possible to develop realistic irradiation models for the early solar system. The uncertainties in the nuclear reaction cross sections for the production of the short-lived nuclides and the exact geometry of an irradiation scenario are probably the other two essential limiting factors in developing realistic irradiation models.

The production of the short-lived nuclides by solar energetic particles has been studied by several groups (Heymann and Dziczkaniec 1976; Clayton et al. 1977; Heymann et al. 1978; Lee 1978; Wasserburg and Arnould 1987; Clayton and Jin 1995a; Goswami et al. 2001; Gounelle et al. 2001, 2006; Leya et al. 2003). Alternatively, several irradiation scenarios prior to the formation of the solar system have also been proposed (Clayton and Jin 1995b; Ramaty et al. 1996) along with the proposed trapping of GCR ^{10}Be nuclei in the collapsing presolar molecular cloud core by Desch et al. (2004). Gounelle et al. (2001, 2006) have recently considered the irradiation of thermally evolved protoCAIs within the magnetic reconnection ring (Shu et al. 2001). Leya et al. (2003) considered numerous short-term (~1 yr) and long-term (~1 Ma) irradiation scenarios involving solar, as well as CAI, composition of gas targets. A short-term intense irradiation scenario was proposed to explain the production of ^7Be .

We have performed detailed numerical simulations of the thermal processing and irradiation of protoCAIs within the X-wind irradiation scenario (Shu et al. 2001; Gounelle et al. 2006). Our goal is to integrate the X-ray flare data of YSOs obtained by the Chandra X-ray satellite (Feigelson et al. 2002a) with the X-wind model (Shu et al. 2001). One of the basic objectives of the simulations is to infer the spread in the final yields of the short-lived nuclides subsequent to the irradiation in the reconnection ring. Comparisons of radionuclide abundances between measurements and predictions serve as a test for our assumptions and for the viability of the model.

Our simulations incorporate simplifying assumptions. The incorporation of radionuclides into CAIs involves numerous physico-chemical processes: condensation, evaporation, coagulation, and irradiation of protoCAIs along their Keplerian orbits through coronal plasma in the reconnection ring. Accurately modeling all these processes is not feasible given our current state of knowledge; nonetheless, our simulations present a general insight into the X-wind irradiation scenario. We believe these results can serve not only as a test of the viability of the basic concepts but also as guidance for subsequent studies. The initial results were reported earlier (Sahijpal 2003; Sahijpal and Soni 2004a, 2004b).

Table 1. Flare characteristics for the simulations.

L_x (ergs s ⁻¹)	Flare area (cm ²)	Ambient temperature (K)		No. of flares ^a	Proton flux ^b ($\gamma = 3$) (cm ⁻² s ⁻¹)	Proton flux ^b ($\gamma = 4$) (cm ⁻² s ⁻¹)
		[$L_p \sim 0.1 L_x$]	[$L_p \sim 0.3 L_x$]		[Lp1]	[Lp1]
10^{34c}	10^{24}	3065	3650		2.8×10^{13}	3.8×10^{13}
10^{33}	2×10^{23}	2610	3100		1.5×10^{13}	2.0×10^{13}
10^{32}	4.6×10^{22}	2100	2500	33	6.2×10^{12}	8.2×10^{12}
10^{31}	10^{22}	1725	2050	539	2.8×10^{12}	3.8×10^{12}
10^{30}	2.2×10^{21}	1420	1700	1077	1.3×10^{12}	1.7×10^{12}
10^{29}	6.0×10^{20}	1100	1310	176	4.7×10^{11}	6.2×10^{11}
10^{28}	1.6×10^{20}	870	1033		1.8×10^{11}	2.4×10^{11}
10^{27}	3.7×10^{19}	700	834		7.7×10^{10}	1.0×10^{11}

^aApproximate number of flares in 5 years of simulation run.

^bEnergy power spectra: $dN \propto E^{-Y} dE$. Flux for energies ≥ 10 MeV/n. Fluxes corresponding to Lp3 flares are three times that of the Lp1 flares.

^cFlare induced for an hour at the end of all simulations.

Flares corresponding to $L_x \sim 10^{27}$ and 10^{28} ergs s⁻¹ were triggered in some of the simulations with an identical occurrence probability.

NUMERICAL SIMULATIONS

The Astrophysical Scenario

The thermal processing and irradiation of protoCAIs take place in the magnetic reconnection ring at the interaction of the circumstellar disc with the protosun's magnetosphere (Shu et al. 1996, 1997, 2001). The interaction occurs at the x-point, a distance $R_x \sim 12 R_\odot$ from the protosun's center. A magnetic reconnection ring $0.25 R_x$ in width is formed in the x-point vicinity. The angular velocity, Ω_x , of the x-point was taken to be 1 day^{-1} . The reconnection ring plasma and its embedded magnetic field lines were considered to be co-rotating with the same angular velocity. In reality, the evolution of magnetic field lines in the reconnection ring is complex (Priest and Forbes 2000).

X-Ray Flare Characteristics

The recently obtained X-ray flare observations of the ONC by the Chandra X-ray satellite were used to model various flare characteristics for simulations (Feigelson et al. 2002a). Simultaneous two- and one-half-day observations of 43 low-mass protostars ($0.7\text{--}1.4 M_\odot$) with theoretical ages <0.3 to 10 Ma in the energy band $0.5\text{--}8$ keV were performed. These measurements indicate strongly elevated and variable X-ray flare luminosities (L_x) in the range of $10^{29}\text{--}10^{31.5}$ ergs s⁻¹ on time scales of 0.5 to >12 h. Approximately 30 flares were observed. The data can be considered equivalent to 86-day and one-half-day observations of a single solar mass protostar with one flare occurring every 1.4 days (Feigelson et al. 2002a). The flares of different X-ray luminosities were grouped together into four primary luminosities, viz., $<\log L_x \text{ (ergs s}^{-1}) > 29, 30, 31, 32$ (31.5 treated as 32 ; see, e.g., Grosso et al. 2004; Wolk et al. 2005). A flare luminosity frequency distribution was obtained to simulate flares of different X-ray luminosities (Table 1). Based on the X-ray luminosities, we made several

approximations in estimating the flare characteristics (Table 1). The influence of these approximations on the final results was also assessed.

Proton Luminosities

The proton luminosities of the simulation flares were estimated based on the modern solar flare observations that indicate an approximate empirical relation, $L_p (\geq 10 \text{ MeV/n}) \sim 0.09 L_x (1.6\text{--}12 \text{ keV})$ (Lee et al. 1998). The $1.6\text{--}12$ keV X-ray energy band used in this relation has to be compared with the Chandra's X-ray energy band of $0.5\text{--}8$ keV. Due to the weak thermal X-ray emissions by the coronal plasma at temperature $\geq 10^7$ K for $\leq 2 \text{ \AA}$ (Mewe et al. 1985; Haisch et al. 1995), the $8\text{--}12$ keV X-rays will not significantly contribute to the total X-ray luminosity. However, the lower X-ray energy band of $0.5\text{--}1.6$ keV, not considered in the empirical relation, could significantly contribute to the total X-ray luminosity. The use of the empirical relation in the energy band of $0.5\text{--}8$ keV could result in overestimating the ($\geq 10 \text{ MeV/n}$) energetic particle fluxes. Based on the continuum of the synthetic energy spectrum of X-ray emission in the case of solar flares (Mewe et al. 1985), the ($\geq 10 \text{ MeV/n}$) fluxes may be overestimated by a factor of $3\text{--}4$. In addition, it has been proposed that the solar proton fluence scale nonlinearly with the X-ray luminosity (Feigelson et al. 2002a). Based on the frequency distribution of solar flares as a function of proton and X-ray energies, an enhancement factor of 10 in the proton fluence for YSOs has been proposed (Feigelson et al. 2002a). This could imply $L_p(\geq 10 \text{ MeV/n})/L_x(0.5\text{--}8 \text{ keV}) \sim 0.3$ (Feigelson et al. 2002a). As there is no astrophysical basis for an assumed enhancement factor of 10 in the proton fluence (Feigelson et al. 2002a), we carried out simulations with two sets of $L_p(\geq 10 \text{ MeV/n})/L_x(0.5\text{--}8 \text{ keV}) = 0.1$ (Lp1, in short) and 0.3 (Lp3, in short). The results obtained from these simulations are finally generalized for a diverse range of L_p/L_x . In the preliminary results (Sahijpal and Soni 2004a, 2004b), we considered an enhancement factor of 10 in the proton fluence (Feigelson et al. 2002a)

along with $L_p(\geq 10 \text{ MeV/n})/L_x(0.5\text{--}8 \text{ keV}) = 0.1$, without considering its associated influence on the deduced ambient temperature attained by protoCAIs. In the present work, we have appropriately rectified the problem by carrying out the simulations for $L_p/L_x = 0.1$ and 0.3 . Since we are ignoring the contributions of the proton fluence from the flares with $L_x \leq 10^{28} \text{ ergs s}^{-1}$ that are below the detection limit of the Chandra X-ray satellite, the estimated proton flux received by protoCAIs could be even higher (Feigelson et al. 2002a). These weak flares could be far more frequent than the strong flares individually studied by the Chandra X-ray satellite (Wolk et al. 2005). The proton fluence contribution from these flares could significantly influence the irradiation of protoCAIs.

Flare Area and the ProtoCAIs' Ambient Temperature

The active reconnection ring areas that receive significant doses of X-ray and energetic particles ($>1 \text{ MeV/n}$) during the flares were estimated by assuming a superflare luminosity ($L_x \sim 10^{34} \text{ ergs s}^{-1}$) (Grosso et al. 1997) spread over the reconnection ring area ($\sim 10^{24} \text{ cm}^2$) (Shu et al. 2001). A typical small flare, e.g., $L_x \sim 10^{31} \text{ ergs s}^{-1}$, was assumed to cover a percentage area of the reconnection ring, i.e., $\sim 10^{22} \text{ cm}^2$ (Shu et al. 2001). Based on these flare areas along with the average flare area estimates of the modern solar flares (Zirin 1988), we deduced the flare areas corresponding to other X-ray luminosities by linear interpolation (Table 1). Modern solar flares can have a spread in the active flare area over a factor of 2. We anticipate at least an identical spread in the deduced flare areas for YSOs. There could be additional uncertainties due to the assumed linear interpolation used in estimating the flare areas for YSOs. These uncertainties are difficult to quantify with our present understanding of YSO flares. This is one of the major limitations of the present work.

The ambient temperature attained by grains during a flare was estimated using the radiative balance criteria (Shu et al. 2001). For L_p1 ($L_p/L_x = 0.1$) flares, an integrated ($>1 \text{ MeV/n}$) energetic particle flux equivalent to the ($0.5\text{--}8 \text{ keV}$) X-ray flux was assumed to deduce the ambient temperature (Shu et al. 2001). For L_p3 ($L_p/L_x = 0.3$) flares, we considered an integrated ($>1 \text{ MeV/n}$) energetic particle flux three times the ($0.5\text{--}8 \text{ keV}$) X-ray flux to deduce the ambient temperature. The grains were assumed to radiate in free space with an emission efficiency of unity (Shu et al. 2001). The estimated ambient temperature based on these assumptions would be the lowest deduced temperature attained by the grains during a flare (Table 1). The temperature in the inner regions of the active flare area could be even higher (Shu et al. 2001). In addition, it should be emphasized that underestimating the reconnection ring area that receives significant doses of X-rays and energetic particles from a flare would result in a relatively higher ambient temperature and a higher energetic particle flux received by the grains, and vice-versa. An increase (decrease) in the flare area by a factor of 2 will result

in 16% decrease (19% increase) in the deduced ambient temperature. This can have a drastic influence on the physico-chemical evolution of grains.

Energetic Particle Spectra and Flux

A power law energy differential spectra ($dN \propto E^{-\gamma} dE$) based on the modern solar flares (Reames et al. 1997) was assumed for estimating the energetic particles' flux (Gounelle et al. 2001; Leya et al. 2003). Even though in the modern solar flares the gradual (GRD) flares contribute significantly to the solar energetic particles compared to the impulsive (IMP) flares (Goswami et al. 2001; Leya et al. 2003), we ran several simulations with IMP and GRD flares to explore the diversity of irradiation. Power spectral indices γ of 3 and 4 were considered for the GRD and IMP flares, respectively (Gounelle et al. 2001). In a couple of simulations, the spectral indices corresponding to the GRD and IMP flares were varied from 2 to 3 and 3 to 4, respectively.

For the impulsive flares, $^3\text{He}/\text{proton}$ and $^4\text{He}/\text{proton}$ ratios of 0.3 and 0.1, respectively, were assumed (Reames et al. 1997; Gounelle et al. 2001), however, there could be large variations in the $^3\text{He}/\text{proton}$ ratio (Reames and Ng 2004). For the gradual flares, a $^4\text{He}/\text{proton}$ ratio of 0.01 (Lang 2000) was chosen. In a couple of simulations, we simulated both GRD and IMP flares with an identical occurrence probability. These simulations are marked as MIX. A GRD/IMP energetic particle fluence ratio spanning over five orders of magnitude was recently analyzed by Leya et al. (2003). Due to the modest number of the total flares triggered in our simulations, we cannot attain significant energetic particle fluences for flares having high GRD/IMP ratios. However, in the MIX simulations, subsequent to the irradiation in the reconnection ring we triggered a GRD superflare to attain higher GRD/IMP energetic particle fluence.

The energetic particle fluxes of the protons ^3He and ^4He corresponding to the GRD and IMP flares were inferred using the estimated flare areas and the estimated proton luminosities (Gounelle et al. 2001). Due to the uncertainties in the estimated flare areas, there would be a minimum uncertainty of a factor of 2 in estimating the energetic particle fluxes. There could be additional uncertainties due to the assumed L_p/L_x . However, the energetic proton flux of $(1\text{--}5) \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to the most frequent flare with $L_x \sim 10^{30} \text{ ergs s}^{-1}$ (Table 1) is identical to the "short-term" intense energetic flux of $2 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ (Leya et al. 2003).

Details of the Numerical Simulations

In most of the simulations, the $0.25 R_x$ -wide reconnection ring was divided into five annular zones of $0.05 R_x$ widths. To study the effect of zone widths, we tried some simulations with the reconnection ring divided into ten zones of $0.025 R_x$ widths. The flares were triggered radially covering all five (ten) annular zones. For a given flare, the

thermal reprocessing of grains and their mixing were carried out independently for the five (ten) annular zones. A flare of a specific L_x , according to the flare luminosity frequency distribution, was triggered randomly at a frequency of 1 day^{-1} , at a random angular coordinate, with a random time span between 1–12 h in most of the simulations. The influence on the final yields of the short-lived nuclides and the thermal processing of grains due to different flaring time spans, e.g., 1–6, 1–12, and 1–24 h, was also studied. The flare's orbital motion was synchronized with the reconnection ring plasma, much as in the modern solar flares. The simulations can be run for a period of 2–3 decades with a time step of an hour.

Orbital Evolution of ProtoCAIs

The simulations were initiated with a uniform distribution of spherical dust grains in the reconnection ring. The grains were assumed to be CI in composition (Taylor 2001) with radii ranging from $32 \mu\text{m}$ to 20 mm (model G32, in short for the grain-size distribution with a minimum grain size of $32 \mu\text{m}$). This grain-size distribution includes eight distinct grain sizes having the radii ratio of $2^{4/3}$ between the two successive sizes. To explore the influence of the grain-size distribution on the thermal processing and the irradiation of protoCAIs in the reconnection ring, we carried out simulations with two additional grain-size distributions, viz., $125 \mu\text{m}$ – 16 mm (model G125, in short for the grain-size distribution with a minimum grain size of $125 \mu\text{m}$) and $500 \mu\text{m}$ – 13 mm (model G500, in short for the grain-size distribution with a minimum grain size of $500 \mu\text{m}$). These grain-size distributions include eight distinct grain sizes having the radii ratio of 2 and $2^{2/3}$, respectively, between the two successive sizes. Around 10^4 coordinates, uniformly distributed throughout the reconnection ring, were seeded with a size distribution of grains, numbering $\sim 10^{10}$ grains per size per coordinate. The grains were introduced in the Keplerian orbits (Shu et al. 2001). Due to the coronal plasma viscous drag experienced by the grains, we appropriately modified their Keplerian orbits by using the theoretical formulation developed by Shu et al. (2001). The residence time of a grain with a radius of 1 cm has been theoretically estimated to be ~ 20 years in the reconnection ring. This was appropriately scaled for the grains of different sizes (Shu et al. 2001).

It is not possible to numerically model the modifications in the orbits of the electrostatically charged grains by the complex magnetic field in the reconnection ring (Priest and Forbes 2000), so we ignored the magnetic effects on the grains. We cannot quantify the associated uncertainties on the results. The magnetic effects would be more prominent on the smaller ($\leq 100 \mu\text{m}$) grains, and would probably reduce their residence time in the reconnection ring (Shu et al. 2001). However, in the simulations with the predominant grains having sizes $> 100 \mu\text{m}$, these effects would be minimal. The

plasma viscous drag alone modifies the Keplerian orbits of the grains, causing them to spiral out of the reconnection ring at $0.75 R_x$, and finally accrete on the protosun. A fresh supply of grains (Lee et al. 1998; Shu et al. 2001) with CI composition was introduced at $0.97 R_x$, with random angular coordinates; each time the processed grains spiraled out of the reconnection ring at $0.75 R_x$. A steady inflow rate of the grains into the reconnection ring was monitored for 100 consecutive days. A correction factor to the inflow rate was evaluated and appropriately applied during the next 100 consecutive days to maintain a steady supply. Simulations with different steady inflow rates, spanning over five orders of magnitude, were run to rule out its dependence on the yields of the short-lived nuclides.

Thermodynamics of the Condensation of ProtoCAIs

The vaporization/condensation of the grains within a flare area was done based on the ambient temperature attained by the grains (Table 1). As the physico-chemical environment(s) prevailing during the flares are uncertain, there could be large associated uncertainties in estimating the dust/gas ratio as well as the partial pressures of the various elemental constituents of the protoCAIs. These uncertainties can have dire consequences on the adopted grain condensation criteria (Yoneda and Grossman 1995; Ebel and Grossman 2000). For the major elemental constituents of the protoCAIs, we adopted the criteria for the condensation of grains in an environment with an enhanced dust/gas ratio of ~ 50 – $100\times$ solar and the total gaseous pressure $P^{\text{tot}} \sim 10^{-3} \text{ atm}$, or an enhanced dust/gas ratio of $> 500\times$ solar and $P^{\text{tot}} \sim 10^{-6} \text{ atm}$ (Yoneda and Grossman 1995; Ebel and Grossman 2000). The total gaseous pressure prevailing in the reconnection ring could be much lower than the assumed values. This can alter the condensation criteria. However, a high dust/gas ratio is essential to have the protoCAIs in the molten state over a larger temperature range to ensure the grain (core-mantle) coagulation proposed by Shu et al. (2001).

The grains (including their refractory components) were completely vaporized at temperatures $\geq 2050 \text{ K}$. The condensations of the refractory elements as CMAS ($\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$) liquids were assumed to commence at temperatures $\geq 1700 \text{ K}$ (Yoneda and Grossman 1995; Ebel and Grossman 2000). This was followed by the condensation of ferromagnesian minerals in the temperature range of 1100 – 1700 K . For the volatile elements S, Mn, K, Na, and Cl, it is extremely difficult to estimate the extent of condensation in the reconnection ring (see, e.g., Desch and Ouellette 2005). However, an estimate can be made for the average ambient temperature prevailing for the dust grains in the reconnection ring. The X-ray flares with luminosities, $L_x \leq 10^{28} \text{ ergs s}^{-1}$ that are below the detectable limit of the Chandra X-ray satellite could be more frequent with YSOs (Feigelson et al. 2002a). It is quite likely that due to these frequent weaker flares the average temperature of the reconnection ring was never less

Table 2. Chemical composition (in %) of protoCAIs corresponding to three models.

Elements	CI comp.	Model-I		Model-II		Model-III	
		Refractory core	Mantle	Refractory core	Mantle	Refractory core	Mantle
Al	0.86	20.99	0.00	13.04	0.00	13.04	0.00
Ca	0.90	21.97	0.00	13.64	0.00	13.64	0.00
Ti	0.04	1.06	0.00	1.06	0.00	1.06	0.00
Mg	9.55	2.79	11.81	5.78	10.45	5.78	10.56
Si	10.67	5.72	13.06	11.30	11.31	11.30	11.43
Fe	18.51	0.00	23.17	0.11	21.09	0.11	21.32
O	46.40	47.47	46.37	55.14	48.65	55.14	49.19
Be	27 ppb	630 ppb	0	630 ppb	0	630 ppb	0
C	3.45	0.00	1.44	0.00	1.44	0.00	1.44
N	0.32	0.00	0.13	0.00	0.13	0.00	0.13
Cl	0.07	0.00	0.03	0.00	0.08	0.00	0.008
S	5.25	0.00	2.19	0.00	5.98	0.00	6.01
Mn	0.20	0.00	0.08	0.00	0.22	0.00	0.023
Cr	0.27	0.00	0.11	0.00	0.30	0.00	0.031
K	0.06	0.00	0.02	0.00	0.07	0.00	0.007
Na	0.48	0.00	0.20	0.00	0.55	0.00	0.056
H	2.02	0.00	0.00	0.00	0.00	0.00	0.00
Total (%)	100.15	100.00	100.00	100.07	100.3	100.07	100.2
Mass (in grams)	1	0.042	0.80	0.066	0.88	0.066	0.87

than 800–1000 K. The uncertainty in estimating this average ambient temperature makes it difficult to accurately model the condensation of volatiles. We considered three distinct chemical compositions to model the condensation of refractory, ferromagnesian, and volatile elements (Table 2). We followed the model-I composition for most of the simulations. With an initial CI elemental abundance of the volatiles, the ferromagnesian mantles of the grains condensed only one-third of the volatiles in the model-I composition. The remaining two-thirds volatile inventory was lost. These volatiles would probably accrete onto the protosun. In model-II and model-III, we varied the chemical composition of the core-mantle assemblages to understand its influence on the final yields of the short-lived nuclides.

Irradiation of ProtoCAIs

The repeated occurrence of flares corresponding to $L_x \sim 10^{31-32}$ ergs s⁻¹ results in an ensemble of refractory cores with ferromagnesian mantles (Shu et al. 2001). The production rates of the short-lived nuclides ⁷Be, ¹⁰Be, ⁴¹Ca, ³⁶Cl, ²⁶Al, and ⁵³Mn were evaluated for the ensemble according to flares luminosities. For the irradiation of the gaseous phases (vapors) generated during a flare, the vapors were treated as 5 μm grains for analytical simplifications. The final yields of the short-lived nuclides were obtained by evolving the ensemble of protoCAIs in the reconnection ring. The production rate of a radionuclide i at a depth x within a grain was estimated using the expression:

$$P_i = N_A \Sigma_j \int A_j^{-1} \times F(E, x) \times C_j \times \sigma(j \rightarrow i, E) dE \quad (1)$$

where $F(E, x)$ represents the energetic particle flux as a

function of energy and depth x within a dust grain, taking into account the ionization losses of the charge particles (Lal 1972; Goswami et al. 2001). N_A is the Avogadro number, A_j is the mass number of the target nuclei, $\sigma(j \rightarrow i, E)$ is the nuclear reaction cross section for the production of the radionuclide i from the stable nuclide j , and C_j is the concentration of the stable nuclei j at the depth x .

Nuclear Reaction Cross Sections

Several proton-, ³He-, and ⁴He-induced nuclear reactions were considered in the simulations (Table 3). The reaction cross sections for the production of ²⁶Al, ⁴¹Ca, and ⁵³Mn by the proton- and ⁴He-induced reactions were taken from Ramaty et al. (1996). The cross sections for the production of ³⁶Cl by the proton- and ⁴He-induced reactions were taken from Goswami et al. 2001 (and the references therein). For the production of ⁷Be and ¹⁰Be, the proton-induced experimental reaction cross sections were taken from Bodemann et al. (1993), Michel et al. (1995), and Schiekel et al. (1996), whereas the ⁴He-induced reaction cross sections were taken from Lange et al. (1995). The estimates of the reaction cross sections for the ³He-induced reactions are mostly theoretical, and were taken from Lee et al. (1998) and Gounelle et al. (2001). However, in the case of the ²⁴Mg(³He, p)²⁶Al reaction, we used the recently obtained experimental reaction cross sections (Fitoussi et al. 2004) which are 2.5 times lower than the theoretical estimates based on statistical models. As the impulsive flares produce ⁴¹Ca largely by the ⁴⁰Ca(³He, 2p)⁴¹Ca reaction, the uncertainties associated with the theoretical estimates of the cross sections could have significant influence on the final yields of ⁴¹Ca. In general, there could be uncertainties in all the reaction cross

Table 3. Reactants with the nuclear reaction cross section references used for the irradiation production of the short-lived nuclides.

Radionuclides	Proton-induced	³ He-induced	⁴ He-induced
⁷ Be	[¹² C, ¹⁴ N, ¹⁶ O, ²⁸ Si, ²⁴ Mg, ²⁷ Al] ^a	Not considered (Low contribution) ^f	[¹² C, ¹⁴ N, ¹⁶ O, ²⁸ Si, ²⁴ Mg, ²⁷ Al] ^b
¹⁰ Be	[¹² C, ¹⁴ N, ¹⁶ O, ²⁸ Si, ²⁴ Mg, ²⁷ Al, ⁵⁶ Fe, ⁵⁸ Ni] ^a	[¹⁶ O] ^g	[¹² C, ¹⁴ N, ¹⁶ O, ²⁸ Si, ²⁴ Mg, ²⁷ Al] ^b
²⁶ Al	[²⁶ Mg, ²⁸ Si, ²⁷ Al] ^c	[²⁷ Al, ²⁸ Si, ²⁵ Mg] ^d [²⁴ Mg] ^e	[²⁴ Mg, ²⁸ Si, ²³ Na, ²⁷ Al] ^c
⁴¹ Ca	[⁴¹ K, ⁴² Ca, ⁴⁴ Ca] ^c	[⁴⁰ Ca] ^d	[³⁹ K, ⁴⁰ Ca] ^c
³⁶ Cl	[³⁶ S, ³⁹ K, ³⁷ Cl] ^c	Not considered	[³³ S, ³⁴ S, ³⁵ Cl] ^c
⁵³ Mn	[⁵³ Cr, ⁵⁴ Fe, ⁵⁷ Fe, ⁵⁵ Mn, ⁵⁶ Fe] ^c	Not considered	[⁵² Cr, ⁵⁴ Fe] ^c

References: a) Bodemann et al. 1993; Michel et al. 1995; Schielke et al. 1996. b) Lange et al. 1995. c) Ramaty et al. 1996; Goswami et al. 2001. d) Lee et al. 1998. e) Fitoussi et al. 2004. f) Gounelle et al. 2003. g) Gounelle et al. 2001.

sections that were estimated theoretically, specifically, the ³He- and ⁴He-induced nuclear reactions (Leya et al. 2003).

One of the shortcomings of the present work is that the production of the short-lived nuclides by secondary protons and neutrons has not been considered. Due to the self-shielding effects, the secondary protons and neutrons (see, e.g., Leya et al. 2000) can contribute to the production of the short-lived nuclides. These effects would be insignificant for the grain-size distributions considered in the present work and are generally ignored (Gounelle et al. 2001; Goswami et al. 2001).

Flare Simulations and the Thermal Processing of ProtoCAIs

The flares corresponding to $L_x \sim 10^{32}$ ergs s⁻¹ (Lp1-model; $L_p/L_x = 0.1$) and $L_x \sim 10^{31-32}$ ergs s⁻¹ (Lp3-model; $L_p/L_x = 0.3$) were assumed to vaporize grains (core-mantle assemblages) completely. This vaporized material within a zonal flare area was homogenized and irradiated. After these strong flares, the refractory cores with typical radii of ~ 50 μ m can condense within half a day, for an assumed average rock surface density (Σ_r) of 1.6 g cm⁻³ in the reconnection ring (Shu et al. 2001). The average rock surface density (Σ_r) varies during the decades-long X-wind cycle (Shu et al. 2001). This will result in a varying refractory condensate size subsequent to the strong flares. For the G32 simulations, we assumed the condensation of refractory cores of radii 32 μ m subsequent to the strong flares. Ca, Al, and Be (along with their radionuclides) in CI proportions were condensed in the refractory cores. These refractory cores were subsequently coated with a ferromagnesian mantle of uniform thickness (Table 2). A mantle thickness in the range of 7 μ m–80 μ m was estimated based on the ferromagnesian inventory of the flare zone and the number of refractory cores. The mantle was grown in the layers of 98 incremental steps with a 10% thickness increase in each step.

For the G125 and G500 simulations, we considered the condensation of refractory cores of sizes 125 μ m and 500 μ m, respectively, subsequent to the strong flares that vaporized the core-mantle assemblages completely. The refractory cores were coated with the ferromagnesian mantles in a way identical to the G32 simulations.

The flares corresponding to $L_x \sim 10^{29-30}$ ergs s⁻¹ (Lp1-model) and $L_x \sim 10^{29}$ ergs s⁻¹ (Lp3-model) were treated

identically for the thermal processing and coagulation of grains. In one of the simulations, the core-mantle assemblages were irradiated without thermal coagulation. However, in the rest of the simulations, we considered grain coagulation. Grains comprising the eight distinct refractory core sizes in the range of 32 μ m–20 mm for the G32 simulations were homogenized and irradiated. A grain-size distribution having distinct cores, along with their mantles, was produced for grain coagulation. A hierarchical coagulation model was formulated whereby a numerical fraction (CF30, the coagulation fraction for $L_x \sim 10^{29-30}$ ergs s⁻¹ flares, a free parameter) of the cores of a specific size, along with their mantles, forms core-mantle grains of the next larger size. As the inferred grain temperatures <1700 K, the coagulation of the core-mantle assemblages was assumed to result in quasi-spherical core-mantle assemblages of larger sizes (Shu et al. 2001). An identical procedure for the coagulation was followed in the G125 and G500 simulations.

Hierarchical coagulation models in which larger clusters grow from the smaller in a hierarchical way (Kornet et al. 2001, 2004; Popolo et al. 2003) have been used in diverse branches of physical sciences. Here the model has been used for computational simplifications. A detailed analysis of the problem would require fractal growth of aggregates to produce fluffy structures (Meakin 1988; Meakin and Donn 1988; Chokshi et al. 1993; Weidenschilling and Ruzmaikina 1994; Shu et al. 2001) during the orbital motion of the protoCAIs. Numerical simulations of the evolution of fractal aggregates alone involve considerable computation (see, e.g., Richardson 1995; Lee 2000). Even the fractal growth of a single grain would be complicated in the present scenario. Prior to a flare, the detailed orbital and the thermal evolutionary history of all the protoCAIs entering into the flare area have to be appropriately accounted for. The hierarchical coagulation model adopted here works on an average statistical behavior of protoCAIs' evolution based on their sizes that determine their orbital motion.

The flares corresponding to $L_x \sim 10^{31}$ ergs s⁻¹ (Lp1-model) and $L_x \sim 10^{30}$ ergs s⁻¹ (Lp3-model) resulted in complete vaporization of mantles. The vapor phase was then irradiated and homogenized. The bare refractory cores were irradiated. According to their sizes, the cores were

homogenized and a core grain-size distribution was obtained for coagulation. A hierarchical coagulation model was formulated whereby a numerical fraction (CF31, the coagulation fraction for $Lx \sim 10^{31}$ ergs s^{-1} flares, a free parameter) of the cores of a specific size forms cores of the next larger size. Subsequent to the flare the refractory cores of distinct sizes were uniformly coated with mantles of 7 μm –80 μm thickness in a way identical to that of the flare corresponding to $Lx \sim 10^{32}$ ergs s^{-1} .

It should be noted that in the Lp1 ($Lp/Lx = 0.1$) simulations, the flare corresponding to $Lx \sim 10^{31}$ ergs s^{-1} occurs on almost every third day over an area ≥ 5 times that of the flares corresponding to $Lx \sim 10^{29-30}$ ergs s^{-1} . This results in a frequent exposure of the grains to the flares with $Lx \geq 10^{31}$ ergs s^{-1} . Hence, the core-mantle coagulation growth based on the core sizes seems to be justified. In the Lp3 ($Lp/Lx = 0.3$) simulations, this assumption is even more appropriate.

In most of the simulations all the thermally unprocessed grains at the time of their maiden exposure to a flare with $Lx \leq 10^{31}$ ergs s^{-1} (Lp1-model) and $Lx \leq 10^{30}$ ergs s^{-1} (Lp3-model) were treated as core-mantle assemblages of 32 μm cores and a mantle thickness of ~ 54 μm (G32-model), in proportion to the Table 2 chemical composition. Identically, in the G125 and G500 simulations, all the thermally unprocessed grains were treated as core-mantle assemblages of 125 μm and 500 μm refractory cores, respectively, with mantle thickness of ~ 220 μm and ~ 870 μm , respectively. This was done for computational simplifications. To explore the influence of this assumption on the simulations, we tried a couple of simulations (G32-1-C and G125-1-B). In these simulations, the thermally unprocessed grains were introduced into the reconnection ring as refractory cores (along with mantles) of different sizes, selected randomly.

In reality, prior to the evolution of the thermally unprocessed grains into core-mantle assemblages, a separate numerical treatment would be required for the thermal evolution and the irradiation of the thermally unprocessed and thermally processed grains. This results in a situation that is beyond the scope of our present computational abilities and memory resources. The computational memory array that is being used presently has to be increased by orders of magnitude to deal with the thermally unprocessed, partially processed, and fully processed (core-mantle assemblages) grains. In addition, it is difficult to numerically consider the coagulation of the thermally processed grains with the thermally unprocessed grains.

RESULTS

Production Rates of the Short-Lived Nuclides

The production rates of the short-lived nuclides for different combinations of core-mantle sizes and the model-I

chemical composition of the protoCAIs is presented in Fig. 1. The production rates were estimated for an hour-long duration of the gradual and impulsive flares corresponding to $Lx \sim 10^{29}$ ergs s^{-1} (Lp1-model). The production rates corresponding to other flare luminosities and the Lp3-model flare luminosities can be calculated by appropriately scaling these production rates (Table 1). The observed ripples in the production rates of some of the short-lived nuclides are the simulation artifacts. The production rates were estimated at 60 distinct depths within a single core-mantle grain, whereas 98 layers of mantle material (with a thickness of 7 μm –80 μm) can be coated on refractory cores, each layer 10% thicker than the previous. The former depth scale is relatively coarse, resulting in an unresolved core-mantle interface during the evaluation of the production rates. The maximum ripples are seen in the production of ^{41}Ca by impulsive flares due to the $^{40}\text{Ca}(^3\text{He}, 2p)^{41}\text{Ca}$ reaction. In general, the ripples are small and the associated effects will not drastically influence the major conclusions drawn from the present work.

Final Irradiation Yields of the Short-Lived Nuclides

The experimental estimates of the various short-lived nuclides in the early solar system are presented in Table 4. The details of the simulations along with the final results are presented in Table 5. To explore the complexity and the diversity of the irradiation environment, more than 35 simulations with a wide range of simulation parameters, including the nature and the intensities of the flares, were done. Columns 2–6 of Table 5 represent the various simulation parameters. In all figures and tables, the mass of the grains is expressed in volumetric units, i.e., $(\text{gm cm}^{-2})^3$ (mass in grams can be obtained by multiplying with a factor of $[4\pi/3\rho^2]$, where ρ is the density of the grains.) A chondritic density of 3.4 gm cm^{-3} was assumed (Goswami et al. 2001; Gounelle et al. 2001). In addition to the average steady mass accretion rate, the influence of the thermal processing of protoCAIs on the accumulation of protoCAIs in the reconnection ring is specified in Table 5. The simulations marked “Accumulation” result in an accumulation growth of the accreting matter (protoCAIs) by the reconnection ring, whereas the simulations marked “steady flow” result in a steady flow of the thermally processed protoCAIs out of the reconnection ring at $0.75 R_x$ to the protosun.

Columns 7–12 of Table 5 represent the final average yields of the short-lived nuclides at the end of simulations. The first row of a simulation result presents the final average yields without the superflare irradiation contribution, whereas the second row includes an hour-long irradiation contribution of a superflare corresponding to $Lx \sim 10^{34}$ ergs s^{-1} . The superflare was triggered at the end of simulations. The nature of the superflare for a simulation is mentioned in the second row of column 6. The core-mantle assemblages were

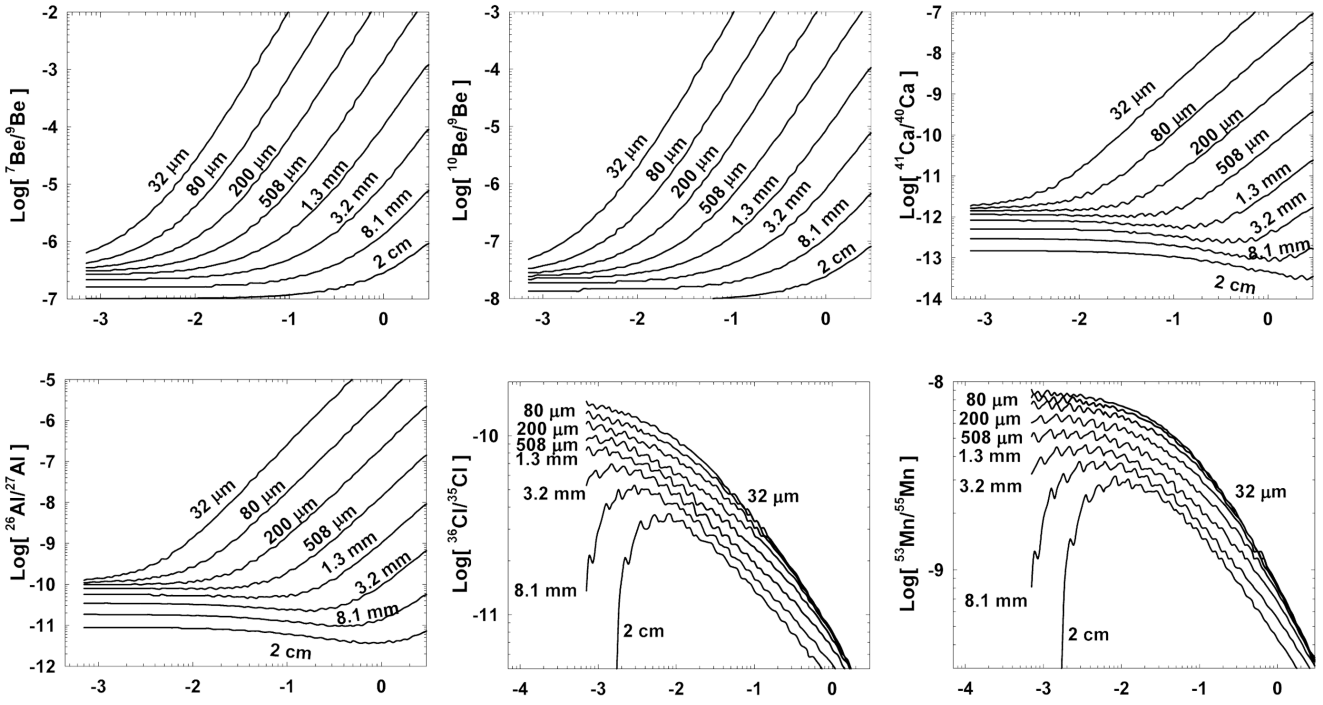
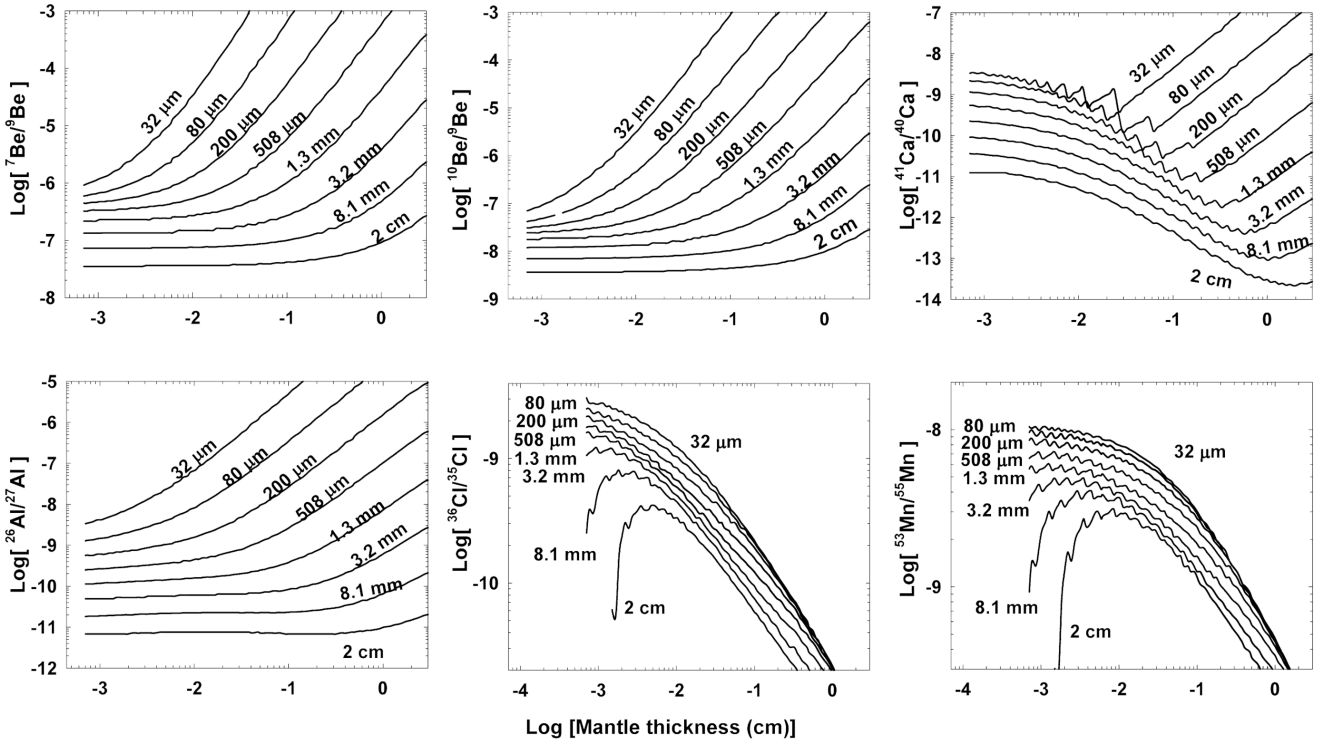
Gradual flares ($\gamma = 3$) ${}^4\text{He}/\text{proton} = 0.01$ **Impulsive flares ($\gamma = 4$)** ${}^3\text{He}/\text{proton} = 0.3$ & ${}^4\text{He}/\text{proton} = 0.1$ 

Fig. 1. The production rates of the short-lived nuclides for gradual flares ($\gamma=3$) and impulsive flares ($\gamma=4$) corresponding to $L_x \sim 10^{29} \text{ ergs s}^{-1}$ and $L_p/L_x \sim 0.1$ (Lp1) for an hour-long exposure. The model-I chemical composition was assumed for the core-mantle assemblages. The different curves represent the production rates for the various core sizes.

Table 4. Adopted reference values of the short-lived nuclides in the early solar system.

Short-lived nuclides	Reference stable nuclides	Adopted initial value	References
^7Be	^9Be	6×10^{-3}	Chaussidon et al. 2004, 2006
^{10}Be	^9Be	$(4-9) \times 10^{-4}$	McKeegan et al. 2000; MacPherson et al. 2003; Desch et al. 2004
^{41}Ca	^{40}Ca	1×10^{-8}	Srinivasan et al. 1996; Sahijpal et al. 2000
^{26}Al	^{27}Al	5×10^{-5}	MacPherson et al. 1995
^{36}Cl	^{35}Cl	$(4-10) \times 10^{-6}$	Lin et al. 2004; Hsu et al. 2006
^{53}Mn	^{55}Mn	2×10^{-5}	Birck et al. 1999 (average CI value)

vaporized during the superflare. The resulting vapors were homogenized and irradiated for an hour.

In most of the simulations, the flares were triggered daily for a random time span of 1–12 h. In simulations G32-1-F and G32-1-G, the flares were triggered for a random time span of 1–6 and 1–24 h, respectively. As mentioned earlier, the X-ray flares corresponding to $L_x \sim 10^{27-28}$ ergs s^{-1} are below the detectable limit of the Chandra X-ray satellite (Feigelson et al. 2002a), but due to their relatively frequent association with the modern sun these flares could be more common in the early solar system. In some of the simulations, G32-1-H-28, G32-1-P-28, G500-1-B-28, G500-3-H-28, and G500-3-I-28, we included the irradiation contribution of these flares. However, due to the absence of any observational data, we modeled these two flares to be occurring with an identical probability throughout the reconnection ring on an integrated time scale comparable to that of the flares with $L_x \sim 10^{29-32}$ ergs s^{-1} .

Most of the simulations were run with a constant coagulation fraction (CF30 and CF31) for the entire range of grain sizes. However, in the G32-1-M and G500-3-D simulations, a variable coagulation index was assumed. Starting from a high coagulation fraction for the smallest cores, the coagulation fraction was lowered by 0.09 for each incremental core size. These simulations promote the assembly of medium-to large-sized cores at the cost of the smaller. In the simulation G32-1-N, grain coagulation was not considered for the flares corresponding to $L_x \sim 10^{29-30}$ ergs s^{-1} .

The differential spectra of the grain size number distribution for a representative set of simulations are presented in Fig. 2. Corresponding to the eight distinct refractory core sizes for the three models, G32, G125, and G500, the ordinates represent the number of grains per mantle size bin. The bin represents 10^x fraction within the range 10^x-10^{x+1} , where x ranges from -3 to 1 or -2 to -1 . For example, in the simulation G32-1-B, the number of grains having $32 \mu\text{m}$ core and $\sim 50 \mu\text{m}$ mantle is $\sim 2 \times 10^{19}$. The differential mass spectra of the final yields of the short-lived nuclides subsequent to the irradiation of protoCAIs in the reconnection ring are presented in Fig. 3. For the short-lived nuclides, ^7Be , ^{10}Be , ^{26}Al , and ^{41}Ca , the ordinates give the integrated refractory core mass (in volumetric units) of the irradiated grains per final yield bin. For example, in the simulation G125-1-A, the integrated refractory core mass

corresponding to the final yield of $1-2 \times 10^{-4}$ for $^{10}\text{Be}/^9\text{Be}$ is $\sim 10^{15}$ vol units. In the case of ^{53}Mn and ^{36}Cl , the ordinates represent the integrated mantle mass of the irradiated grains per final yield bin.

Influence of the Grain-Size Distribution on Mass Accumulation in the Reconnection Ring

Invariably in all the G32 (grain-size distribution with core sizes $32 \mu\text{m}$ – 20mm) simulations, no net accumulation of (protoCAIs) mass by the reconnection ring was observed with the wide range of simulation parameters. On account of the coronal plasma viscous drag, the reconnection ring loses mass to the protosun at a rate that is equivalent to its mass accretion rate. The results were found to be independent of a specific choice of the average mass accretion rates, spanning over five orders of magnitude, as inferred from the simulations G32-1-A, G32-1-B, and G32-1-I (Table 5). An identical result was found even in the simulation G32-1-C, where all the thermally unprocessed grains were introduced in the reconnection ring as refractory cores (along with mantles) of different sizes within the $32 \mu\text{m}$ – 8.1mm range. The steady inflow as well as the outflow of mass through the reconnection ring in the G32 simulations could be accounted for by the differential grain size number distribution spectra (Fig. 2) that are predominant in the grains with sizes $\leq 150 \mu\text{m}$. These grains have a residence time of ≤ 100 days in the reconnection ring. It should be noted that incorporation of magnetic effects would further reduce the residence time of these small grains.

In the G125 and G500 simulations (grain-size distributions with core sizes $125 \mu\text{m}$ – 16mm and $500 \mu\text{m}$ – 13mm , respectively), a net accumulation of protoCAIs' mass by the reconnection ring was observed. For the mass accretion rates considered in the present work, we observed a net mass enhancement by 20, 80, 8, and 200% for the simulations G125-1-A, G500-1-A, G125-3-A, and G500-3-F, respectively, during the five years of the simulation runs. In the simulation G125-1-B, where all the thermally unprocessed grains were introduced into the reconnection ring as refractory cores (along with mantles) of different sizes within the $125 \mu\text{m}$ – 8mm range, a net mass enhancement of 37% was observed in the five years simulation run. This has to be compared with the 20% mass enhancement for simulation G125-1-A. The accumulation of mass by the reconnection ring in all the G125 and G500 simulations

Table 5a. Final average yields of short-lived nuclei for simulations with $Lp/Lx \sim 0.1$ (Lp1).

Models ^a	No. of zonal divisions	Time (years)	CF30 and CF31 coagulation	Accreting mass	Nature of flares ^c	¹⁰ Be/ ⁹ Be	⁴¹ Ca/ ⁴⁰ Ca	²⁶ Al/ ²⁷ Al	⁷ Be/ ⁹ Be	⁵³ Mn/ ⁵⁵ Mn	³⁶ Cl/ ³⁵ Cl
						Adopted initial values ^b					
						(4–9) × 10 ^{−4}	1 × 10 ^{−8}	5 × 10 ^{−5}	6 × 10 ^{−3}	2 × 10 ^{−5}	(4–10) × 10 ^{−6}
G32-1	Core sizes: 32 μm–20 mm										
G32-1-A	5	5	0.2	5 × 10 ¹³	IMP	3 × 10 ^{−5}	7 × 10 ^{−8}	3 × 10 ^{−6}	5 × 10 ^{−5}	7 × 10 ^{−8}	2 × 10 ^{−8}
G32-1-B	5	20	0.2	Steady flow	IMP ^d	8 × 10 ^{−5}	6 × 10 ^{−7}	7 × 10 ^{−6}	6 × 10 ^{−4}	8 × 10 ^{−7}	4 × 10 ^{−7}
				5 × 10 ¹⁵	IMP	3 × 10 ^{−5}	8 × 10 ^{−8}	3 × 10 ^{−6}	4 × 10 ^{−5}	5 × 10 ^{−8}	2 × 10 ^{−8}
G32-1-C	5	10	0.2	Steady flow	IMP ^d	8 × 10 ^{−5}	7 × 10 ^{−7}	7 × 10 ^{−6}	6 × 10 ^{−4}	8 × 10 ^{−7}	4 × 10 ^{−7}
				8 × 10 ¹⁵	IMP	4 × 10 ^{−5}	4 × 10 ^{−8}	4 × 10 ^{−6}	5 × 10 ^{−5}	3 × 10 ^{−7}	1 × 10 ^{−7}
G32-1-D-II	5	10	0.2	Steady flow	IMP ^d	6 × 10 ^{−5}	6 × 10 ^{−7}	6 × 10 ^{−6}	3 × 10 ^{−4}	1 × 10 ^{−6}	5 × 10 ^{−7}
				6 × 10 ¹⁵	IMP	3 × 10 ^{−5}	3 × 10 ^{−7}	4 × 10 ^{−6}	6 × 10 ^{−5}	8 × 10 ^{−8}	8 × 10 ^{−8}
G32-1-E-III	5	5	0.2	Steady flow	IMP ^d	6 × 10 ^{−5}	8 × 10 ^{−7}	8 × 10 ^{−6}	5 × 10 ^{−4}	5 × 10 ^{−7}	4 × 10 ^{−7}
				6 × 10 ¹⁵	IMP	2 × 10 ^{−5}	8 × 10 ^{−8}	3 × 10 ^{−6}	4 × 10 ^{−5}	3 × 10 ^{−7}	3 × 10 ^{−7}
G32-1-F	5	5	0.2	Steady flow	IMP ^d	5 × 10 ^{−5}	7 × 10 ^{−7}	8 × 10 ^{−6}	4 × 10 ^{−4}	3 × 10 ^{−6}	4 × 10 ^{−6}
				5 × 10 ¹⁵	IMP	8 × 10 ^{−6}	3 × 10 ^{−8}	8 × 10 ^{−7}	4 × 10 ^{−5}	5 × 10 ^{−8}	2 × 10 ^{−8}
G32-1-G	5	5	0.2	Steady flow	IMP ^d	8 × 10 ^{−5}	6 × 10 ^{−7}	7 × 10 ^{−6}	8 × 10 ^{−4}	8 × 10 ^{−7}	4 × 10 ^{−7}
				5 × 10 ¹⁵	IMP	4 × 10 ^{−5}	2 × 10 ^{−7}	3 × 10 ^{−6}	8 × 10 ^{−5}	3 × 10 ^{−7}	5 × 10 ^{−8}
G32-1-H-28	5	5	0.2	Steady flow	IMP ^d	8 × 10 ^{−5}	8 × 10 ^{−7}	7 × 10 ^{−6}	5 × 10 ^{−4}	8 × 10 ^{−7}	4 × 10 ^{−7}
				5 × 10 ¹⁵	IMP	4 × 10 ^{−5}	8 × 10 ^{−8}	3 × 10 ^{−6}	2 × 10 ^{−4}	3 × 10 ^{−7}	5 × 10 ^{−8}
G32-1-I	5	10	0.2	Steady flow	IMP ^d	8 × 10 ^{−5}	7 × 10 ^{−7}	8 × 10 ^{−6}	7 × 10 ^{−4}	8 × 10 ^{−7}	4 × 10 ^{−7}
				5 × 10 ¹⁸	IMP	3 × 10 ^{−5}	8 × 10 ^{−8}	3 × 10 ^{−6}	5 × 10 ^{−5}	6 × 10 ^{−8}	2 × 10 ^{−8}
G32-1-J	5	13	0.02	Steady flow	IMP ^d	8 × 10 ^{−5}	7 × 10 ^{−7}	7 × 10 ^{−6}	6 × 10 ^{−4}	8 × 10 ^{−7}	4 × 10 ^{−7}
				5 × 10 ¹⁵	IMP	2 × 10 ^{−5}	8 × 10 ^{−8}	2 × 10 ^{−6}	2 × 10 ^{−4}	2 × 10 ^{−7}	8 × 10 ^{−8}
G32-1-K	5	20	0.6	Steady flow	IMP ^d	8 × 10 ^{−5}	7 × 10 ^{−7}	8 × 10 ^{−6}	8 × 10 ^{−4}	8 × 10 ^{−7}	4 × 10 ^{−7}
				5 × 10 ¹⁵	IMP	3 × 10 ^{−5}	2 × 10 ^{−7}	3 × 10 ^{−6}	5 × 10 ^{−5}	2 × 10 ^{−7}	6 × 10 ^{−8}
G32-1-L	5	7	0.8	Steady flow	IMP ^d	5 × 10 ^{−5}	8 × 10 ^{−7}	4 × 10 ^{−6}	3 × 10 ^{−4}	8 × 10 ^{−7}	4 × 10 ^{−7}
				5 × 10 ¹⁵	IMP	3 × 10 ^{−5}	2 × 10 ^{−7}	3 × 10 ^{−6}	3 × 10 ^{−5}	3 × 10 ^{−7}	3 × 10 ^{−7}
G32-1-M	5	5	Variable 0.9–0.2	Steady flow	IMP ^d	4 × 10 ^{−5}	8 × 10 ^{−7}	3 × 10 ^{−6}	2 × 10 ^{−4}	8 × 10 ^{−7}	7 × 10 ^{−7}
				2 × 10 ¹⁴	IMP	3 × 10 ^{−5}	2 × 10 ^{−7}	3 × 10 ^{−6}	4 × 10 ^{−5}	3 × 10 ^{−7}	8 × 10 ^{−8}
G32-1-N	5	10	CF31 = 0.2 CF30 = 0	Steady flow	IMP ^d	5 × 10 ^{−5}	7 × 10 ^{−7}	4 × 10 ^{−6}	3 × 10 ^{−4}	8 × 10 ^{−7}	4 × 10 ^{−7}
				5 × 10 ¹⁵	IMP	3 × 10 ^{−5}	6 × 10 ^{−8}	3 × 10 ^{−6}	5 × 10 ^{−5}	5 × 10 ^{−8}	2 × 10 ^{−8}
G32-1-O	5	20	0.2	Steady flow	IMP ^d	8 × 10 ^{−5}	6 × 10 ^{−7}	8 × 10 ^{−6}	7 × 10 ^{−4}	8 × 10 ^{−7}	4 × 10 ^{−7}
				5 × 10 ¹⁵	GRD01	2 × 10 ^{−5}	3 × 10 ^{−10}	2 × 10 ^{−8}	4 × 10 ^{−5}	7 × 10 ^{−8}	2 × 10 ^{−9}
G32-1-P-28	5	5	0.2	Steady flow	GRD01 ^d	3 × 10 ^{−5}	6 × 10 ^{−10}	4 × 10 ^{−8}	3 × 10 ^{−4}	6 × 10 ^{−7}	2 × 10 ^{−8}
				5 × 10 ¹⁵	MIX (1:1)	4 × 10 ^{−5}	6 × 10 ^{−8}	2 × 10 ^{−6}	8 × 10 ^{−5}	3 × 10 ^{−7}	3 × 10 ^{−8}
G32-1-Q	10	5	0.2	Steady flow	GRD01 ^d	6 × 10 ^{−5}	6 × 10 ^{−8}	2 × 10 ^{−6}	4 × 10 ^{−4}	8 × 10 ^{−7}	3 × 10 ^{−8}
				5 × 10 ¹⁵	IMP	2 × 10 ^{−5}	6 × 10 ^{−8}	2 × 10 ^{−6}	8 × 10 ^{−5}	8 × 10 ^{−8}	3 × 10 ^{−8}
				Steady flow	IMP ^d	8 × 10 ^{−5}	6 × 10 ^{−7}	7 × 10 ^{−6}	7 × 10 ^{−4}	8 × 10 ^{−7}	4 × 10 ^{−7}
G125-1	Core sizes: 125 μm–16 mm										
G125-1-A	5	5	0.2	8 × 10 ¹⁵	IMP	8 × 10 ^{−5}	3 × 10 ^{−7}	8 × 10 ^{−6}	2 × 10 ^{−4}	8 × 10 ^{−7}	3 × 10 ^{−7}
				Accumulation	IMP ^d	1 × 10 ^{−4}	8 × 10 ^{−7}	1 × 10 ^{−5}	7 × 10 ^{−4}	2 × 10 ^{−6}	7 × 10 ^{−7}
G125-1-B	5	5	0.2	8 × 10 ¹⁵	IMP	8 × 10 ^{−5}	3 × 10 ^{−7}	7 × 10 ^{−6}	1 × 10 ^{−4}	9 × 10 ^{−7}	3 × 10 ^{−7}
				Accumulation	IMP ^d	1 × 10 ^{−4}	9 × 10 ^{−7}	1 × 10 ^{−5}	6 × 10 ^{−4}	2 × 10 ^{−6}	7 × 10 ^{−7}
G500-1	Core sizes: 500 μm–13 mm										
G500-1-A	5	5	0.2	1.5 × 10 ¹⁵	IMP	2 × 10 ^{−4}	1 × 10 ^{−6}	2 × 10 ^{−5}	2 × 10 ^{−4}	3 × 10 ^{−6}	1 × 10 ^{−6}
				Accumulation	IMP ^d	3 × 10 ^{−4}	2 × 10 ^{−6}	3 × 10 ^{−5}	8 × 10 ^{−4}	4 × 10 ^{−6}	2 × 10 ^{−6}

Table 5a. *Continued.* Final average yields of short-lived nuclei for simulations with $Lp/Lx \sim 0.1$ (Lp1).

Models ^a	No. of zonal divisions	Time (years)	CF30 and CF31 coagulation	Accreting mass	Nature of flares ^c	¹⁰ Be/ ⁹ Be	⁴¹ Ca/ ⁴⁰ Ca	²⁶ Al/ ²⁷ Al	⁷ Be/ ⁹ Be	⁵³ Mn/ ⁵⁵ Mn	³⁶ Cl/ ³⁵ Cl
						Adopted initial values ^b					
						$(4-9) \times 10^{-4}$	1×10^{-8}	5×10^{-5}	6×10^{-3}	2×10^{-5}	$(4-10) \times 10^{-6}$
G500-1-B-28	5	2	0.2	1.5×10^{15}	IMP	5×10^{-4}	5×10^{-7}	2×10^{-5}	6×10^{-4}	4×10^{-6}	8×10^{-7}
				Accumulation	IMP ^d	5×10^{-4}	1×10^{-6}	2×10^{-5}	1×10^{-3}	4×10^{-6}	1×10^{-6}

^aThe simulations are titled according to the choice of some parameters. These parameters are separated by hyphens. In order these are: i) The grain-size distribution among the G32, G125, and G500 models. ii) The Lp/Lx ratio [“1” for $Lp/Lx = 0.1$, and “3” for $Lp/Lx = 0.3$]. iii) An alphabetic sequence. iv) The fourth position marks the basic difference regarding the choice of the simulation. The “28” in this position indicates the inclusion of flares corresponding to $Lx \sim 10^{27-28}$ ergs s⁻¹ in the simulations. The model-II and model-III chemical compositions of protoCAIs are also indicated for some simulations. The model-I chemical composition was assumed for the remaining simulations.

^bExperimental estimates of the short-lived nuclides.

^c⁴He/proton = 0.01 for the gradual (GRD01) flares; ³He/proton = 0.3 and ⁴He/proton = 0.1 for the impulsive (IMP) flares. MIX simulates gradual (GRD01) and impulsive flares with an identical occurrence probability.

^dThe nature of the superflare ($Lx \sim 10^{34}$ ergs s⁻¹).

Columns 2–6 represent the various simulation parameters. In order, these are the number of concentric zonal divisions of the reconnection ring, the simulation time (in years), the numerical coagulation fraction (CF30 and CF31; free parameters), an average steady mass accretion rate that is monitored as the total mass of the grains (in the volumetric units; see text) accreted by the reconnection ring in 100 days, the nature of the flares during simulation. Columns 7–12 represent the final average yields of the short-lived nuclides at the end of simulations. The first row of a simulation result presents the final average yields without the superflare irradiation contribution, whereas the second row includes an hour-long irradiation contribution of a superflare.

Table 5b. Final average yields of short-lived nuclei for simulations with $Lp/Lx \sim 0.3$ (Lp3).

Models ^a	No. of zonal divisions	Time (years)	CF30 and CF31 coagulation	Accreting mass	Nature of flares ^a	¹⁰ Be/ ⁹ Be	⁴¹ Ca/ ⁴⁰ Ca	²⁶ Al/ ²⁷ Al	⁷ Be/ ⁹ Be	⁵³ Mn/ ⁵⁵ Mn	³⁶ Cl/ ³⁵ Cl
						Adopted initial values ^b					
						(4–9) × 10 ^{−4}	1 × 10 ^{−8}	5 × 10 ^{−5}	6 × 10 ^{−3}	2 × 10 ^{−5}	(4–10) × 10 ^{−6}
G32-3 Core sizes: 32 μm–20 mm											
G32-3-A	5	5	0.2	6 × 10 ¹⁵	IMP	3 × 10 ^{−5}	2 × 10 ^{−7}	3 × 10 ^{−6}	2 × 10 ^{−4}	3 × 10 ^{−7}	1 × 10 ^{−7}
				Steady flow	IMP ^d	2 × 10 ^{−4}	2 × 10 ^{−6}	2 × 10 ^{−5}	3 × 10 ^{−3}	3 × 10 ^{−6}	1 × 10 ^{−6}
G32-3-B	5	10	0.7	6 × 10 ¹⁵	IMP	5 × 10 ^{−5}	6 × 10 ^{−7}	5 × 10 ^{−6}	4 × 10 ^{−4}	5 × 10 ^{−7}	2 × 10 ^{−7}
				Steady flow	IMP ^b	2 × 10 ^{−4}	2 × 10 ^{−6}	2 × 10 ^{−5}	2 × 10 ^{−3}	3 × 10 ^{−6}	1 × 10 ^{−6}
G32-3-C-II	5	10	0.2	6 × 10 ¹⁵	IMP	2 × 10 ^{−5}	2 × 10 ^{−7}	2 × 10 ^{−6}	9 × 10 ^{−5}	7 × 10 ^{−8}	6 × 10 ^{−8}
				Steady flow	IMP ^d	1 × 10 ^{−4}	2 × 10 ^{−6}	2 × 10 ^{−5}	1 × 10 ^{−3}	1 × 10 ^{−6}	1 × 10 ^{−6}
G32-3-D	5	5	0.7	6 × 10 ¹⁵	MIX (1:1)	2 × 10 ^{−5}	1 × 10 ^{−7}	1 × 10 ^{−6}	2 × 10 ^{−4}	3 × 10 ^{−7}	6 × 10 ^{−8}
				Steady flow	GRD01 ^d	1 × 10 ^{−4}	1 × 10 ^{−7}	2 × 10 ^{−6}	1 × 10 ^{−3}	2 × 10 ^{−6}	1 × 10 ^{−7}
G125-3 Core sizes: 125 μm–16 mm											
G125-3-A	5	2	0.2	1 × 10 ¹⁶	IMP	1 × 10 ^{−4}	7 × 10 ^{−7}	1 × 10 ^{−5}	4 × 10 ^{−4}	1 × 10 ^{−6}	5 × 10 ^{−7}
				Accumulation	IMP ^d	3 × 10 ^{−4}	2 × 10 ^{−6}	3 × 10 ^{−5}	3 × 10 ^{−3}	4 × 10 ^{−6}	2 × 10 ^{−6}
G500-3 Core sizes: 500 μm–13 mm											
G500-3-A	5	2	0.02	3 × 10 ¹⁵	IMP	5 × 10 ^{−4}	3 × 10 ^{−6}	5 × 10 ^{−5}	8 × 10 ^{−4}	6 × 10 ^{−6}	2 × 10 ^{−6}
				Accumulation	IMP ^d	7 × 10 ^{−4}	5 × 10 ^{−6}	7 × 10 ^{−5}	4 × 10 ^{−3}	9 × 10 ^{−6}	3 × 10 ^{−6}
G500-3-B	5	2	0.2	3 × 10 ¹⁵	IMP	4 × 10 ^{−4}	2 × 10 ^{−6}	4 × 10 ^{−5}	6 × 10 ^{−4}	4 × 10 ^{−6}	2 × 10 ^{−6}
				Accumulation	IMP ^d	6 × 10 ^{−4}	4 × 10 ^{−6}	6 × 10 ^{−5}	3 × 10 ^{−3}	7 × 10 ^{−6}	3 × 10 ^{−6}
G500-3-C	5	2	0.5	3 × 10 ¹⁵	IMP	5 × 10 ^{−4}	4 × 10 ^{−6}	5 × 10 ^{−5}	1 × 10 ^{−3}	6 × 10 ^{−6}	2 × 10 ^{−6}
				Accumulation	IMP ^d	8 × 10 ^{−4}	5 × 10 ^{−6}	7 × 10 ^{−5}	4 × 10 ^{−3}	9 × 10 ^{−6}	4 × 10 ^{−6}
G500-3-D	5	2	Variable 0.7–0.1	3 × 10 ¹⁵	IMP	6 × 10 ^{−4}	4 × 10 ^{−6}	6 × 10 ^{−5}	1 × 10 ^{−3}	8 × 10 ^{−6}	3 × 10 ^{−6}
				Accumulation	IMP ^d	9 × 10 ^{−4}	6 × 10 ^{−6}	8 × 10 ^{−5}	4 × 10 ^{−3}	1 × 10 ^{−5}	4 × 10 ^{−6}

Table 5b. *Continued.* Final average yields of short-lived nuclei for simulations with $Lp/Lx \sim 0.3$ (Lp3).

Models ^a	No. of zonal divisions	Time (years)	CF30 and CF31 coagulation	Accreting mass	Nature of flares ^c	¹⁰ Be/ ⁹ Be	⁴¹ Ca/ ⁴⁰ Ca	²⁶ Al/ ²⁷ Al	⁷ Be/ ⁹ Be	⁵³ Mn/ ⁵⁵ Mn	³⁶ Cl/ ³⁵ Cl
						(4–9) × 10 ^{−4}	1 × 10 ^{−8}	5 × 10 ^{−5}	6 × 10 ^{−3}	2 × 10 ^{−5}	(4–10) × 10 ^{−6}
G500-3-E	5	2	0.2	3 × 10 ¹⁵	γ = 2 & 3	4 × 10 ^{−4}	2 × 10 ^{−9}	2 × 10 ^{−7}	7 × 10 ^{−4}	3 × 10 ^{−6}	4 × 10 ^{−8}
				Accumulation	GRD01 ^d	6 × 10 ^{−4}	4 × 10 ^{−9}	3 × 10 ^{−7}	2 × 10 ^{−3}	5 × 10 ^{−6}	9 × 10 ^{−8}
G500-3-F	5	5	0.2	4 × 10 ¹⁵	γ = 3 & 4	9 × 10 ^{−4}	2 × 10 ^{−6}	4 × 10 ^{−5}	1 × 10 ^{−3}	6 × 10 ^{−6}	2 × 10 ^{−6}
				Accumulation	IMP ^d	1 × 10 ^{−3}	4 × 10 ^{−6}	6 × 10 ^{−5}	4 × 10 ^{−3}	9 × 10 ^{−6}	3 × 10 ^{−6}
G500-3-G	5	2	0.2	3 × 10 ¹⁵	MIX (1:1)	2 × 10 ^{−4}	9 × 10 ^{−7}	1 × 10 ^{−5}	4 × 10 ^{−4}	3 × 10 ^{−6}	7 × 10 ^{−7}
				Accumulation	GRD01 ^d	4 × 10 ^{−4}	9 × 10 ^{−7}	1 × 10 ^{−5}	2 × 10 ^{−3}	5 × 10 ^{−6}	8 × 10 ^{−7}
G500-3-H-28	5	2	0.2	3 × 10 ¹⁵	IMP	2 × 10 ^{−3}	2 × 10 ^{−6}	4 × 10 ^{−5}	3 × 10 ^{−3}	1 × 10 ^{−5}	2 × 10 ^{−6}
				Accumulation	IMP ^d	2 × 10 ^{−3}	4 × 10 ^{−6}	7 × 10 ^{−5}	5 × 10 ^{−3}	1 × 10 ^{−5}	3 × 10 ^{−6}
G500-3-I-28	5	2	0.2	3 × 10 ¹⁵	MIX (1:1)	1 × 10 ^{−3}	9 × 10 ^{−7}	1 × 10 ^{−5}	3 × 10 ^{−3}	1 × 10 ^{−5}	8 × 10 ^{−7}
				Accumulation	GRD01 ^d	1 × 10 ^{−3}	9 × 10 ^{−7}	7 × 10 ^{−5}	5 × 10 ^{−3}	1 × 10 ^{−5}	8 × 10 ^{−7}
G500-3-J-II	5	2	0.2	3 × 10 ¹⁵	IMP	3 × 10 ^{−4}	3 × 10 ^{−6}	4 × 10 ^{−5}	5 × 10 ^{−4}	2 × 10 ^{−6}	2 × 10 ^{−6}
				Accumulation	IMP ^d	4 × 10 ^{−4}	4 × 10 ^{−6}	7 × 10 ^{−5}	2 × 10 ^{−3}	3 × 10 ^{−6}	3 × 10 ^{−6}
G500-3-K-III	5	2	0.2	3 × 10 ¹⁵	IMP	3 × 10 ^{−4}	3 × 10 ^{−6}	4 × 10 ^{−5}	5 × 10 ^{−4}	1 × 10 ^{−5}	2 × 10 ^{−5}
				Accumulation	IMP ^d	4 × 10 ^{−4}	4 × 10 ^{−6}	6 × 10 ^{−5}	2 × 10 ^{−3}	2 × 10 ^{−5}	3 × 10 ^{−5}

^aThe simulations are titled according to the choice of some parameters. These parameters are separated by hyphens. In order these are: i) the grain-size distribution among the G32, G125 and G500 models. ii) The Lp/Lx ratio [“1” for $Lp/Lx = 0.1$, and “3” for $Lp/Lx = 0.3$]. iii) An alphabetic sequence. iv) The fourth position marks the basic difference regarding the choice of the simulation. The “28” in this position indicates the inclusion of flares corresponding to $Lx \sim 10^{27-28}$ ergs s^{−1} in the simulations. The model-II and model-III chemical compositions of protoCAIs are also indicated for some simulations. The model-I chemical composition was assumed for the remaining simulations.

^bExperimental estimates of the short-lived nuclides.

^c⁴He/proton = 0.01 for the gradual (GRD01) flares; ³He/proton = 0.3 and ⁴He/proton = 0.1 for the impulsive (IMP) flares. MIX simulates gradual (GRD01) and impulsive flares with an identical occurrence probability.

^dThe nature of the superflare ($Lx \sim 10^{34}$ ergs s^{−1}).

Columns 2–6 represent the various simulation parameters. In order, these are the number of concentric zonal divisions of the reconnection ring, the simulation time (in years), the numerical coagulation fraction (CF30 and CF31; free parameters), an average steady mass accretion rate that is monitored as the total mass of the grains (in the volumetric units; see text) accreted by the reconnection ring in 100 days, the nature of the flares during simulation. Columns 7–12 represent the final average yields of the short-lived nuclides at the end of simulations. The first row of a simulation result presents the final average yields without the superflare irradiation contribution, whereas the second row includes an hour-long irradiation contribution of a superflare.

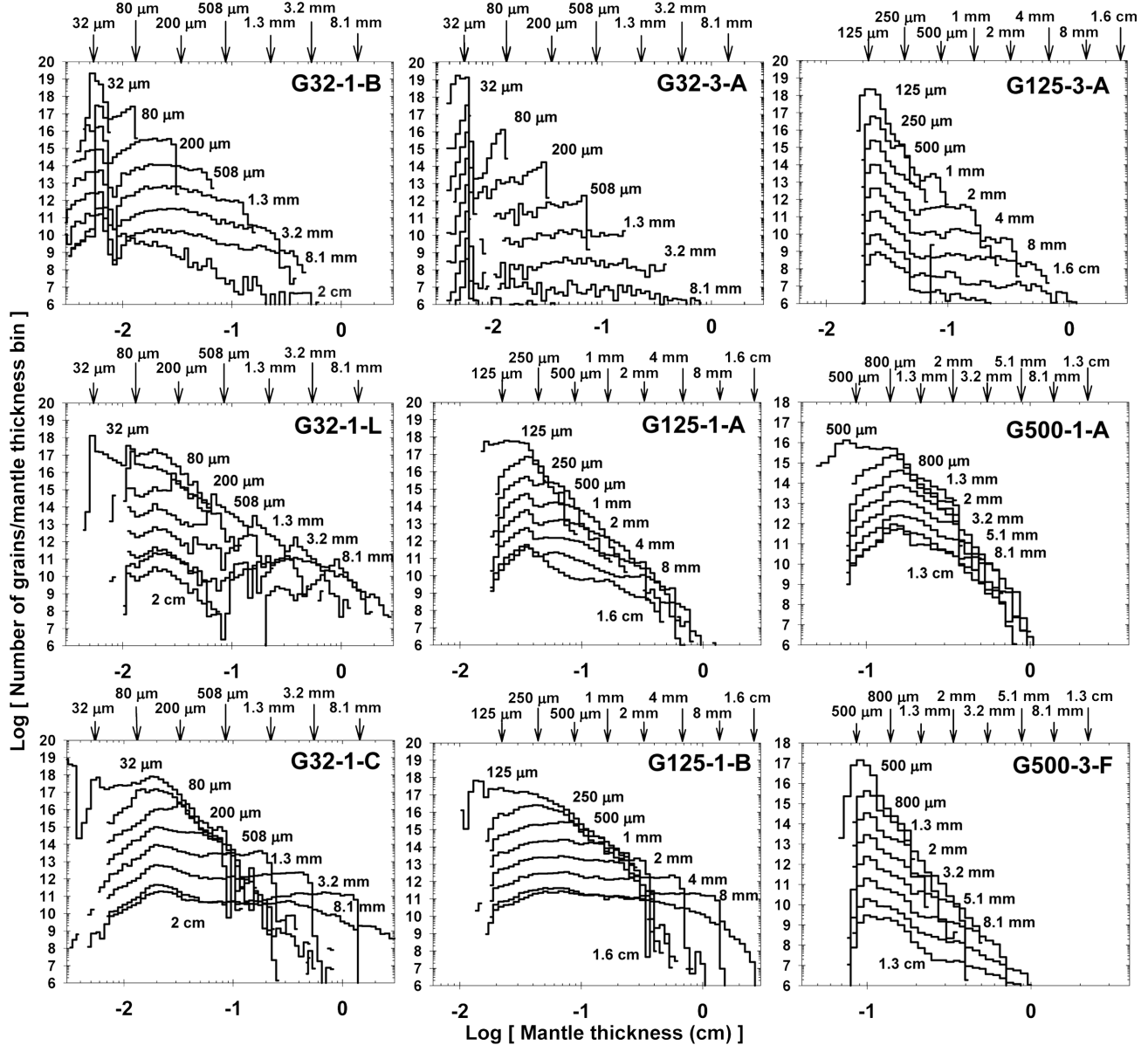


Fig. 2. The differential spectra of the grain-size number distribution for the various core sizes in a representative set of simulations. The marked arrows represent the expected ferromagnesian mantle sizes for the various specified refractory cores. These were estimated by assuming the model-I chemical composition.

results from the differential grain-size number distribution spectra (Fig. 2) that are predominant in the grains with sizes $\geq 300 \mu\text{m}$ and $>1 \text{ mm}$, for G125 and G500 simulations, respectively. These grains have residence times >200 days and >2 years, respectively, and result in mass accumulation by the reconnection ring.

Influence of the Grain-Size Distribution on the Final Average Yields of the Short-Lived Nuclides

The final average yields of the short-lived nuclides in the G32 simulations are one to two orders of magnitude low compared to their experimental estimates in the early solar

system (Table 4). However, the inferred $^{41}\text{Ca}/^{40}\text{Ca}$ in the impulsive flare simulations can explain the observed early solar system value. The average yields of the short-lived nuclides were found to remain constant with time in all the G32 simulations. The influence of the flaring time span on the simulations was found to be negligible. Within a factor of two, simulations G32-1-F and G32-1-G yielded almost identical results compared to simulation G32-1-B. However, the final average yields of $^{53}\text{Mn}/^{55}\text{Mn}$ and $^{36}\text{Cl}/^{35}\text{Cl}$ in the G32-1-G simulation were found to be higher by a factor of 4 and 3, respectively, compared to simulation G32-1-B. The differences in the trends observed for the final average yields

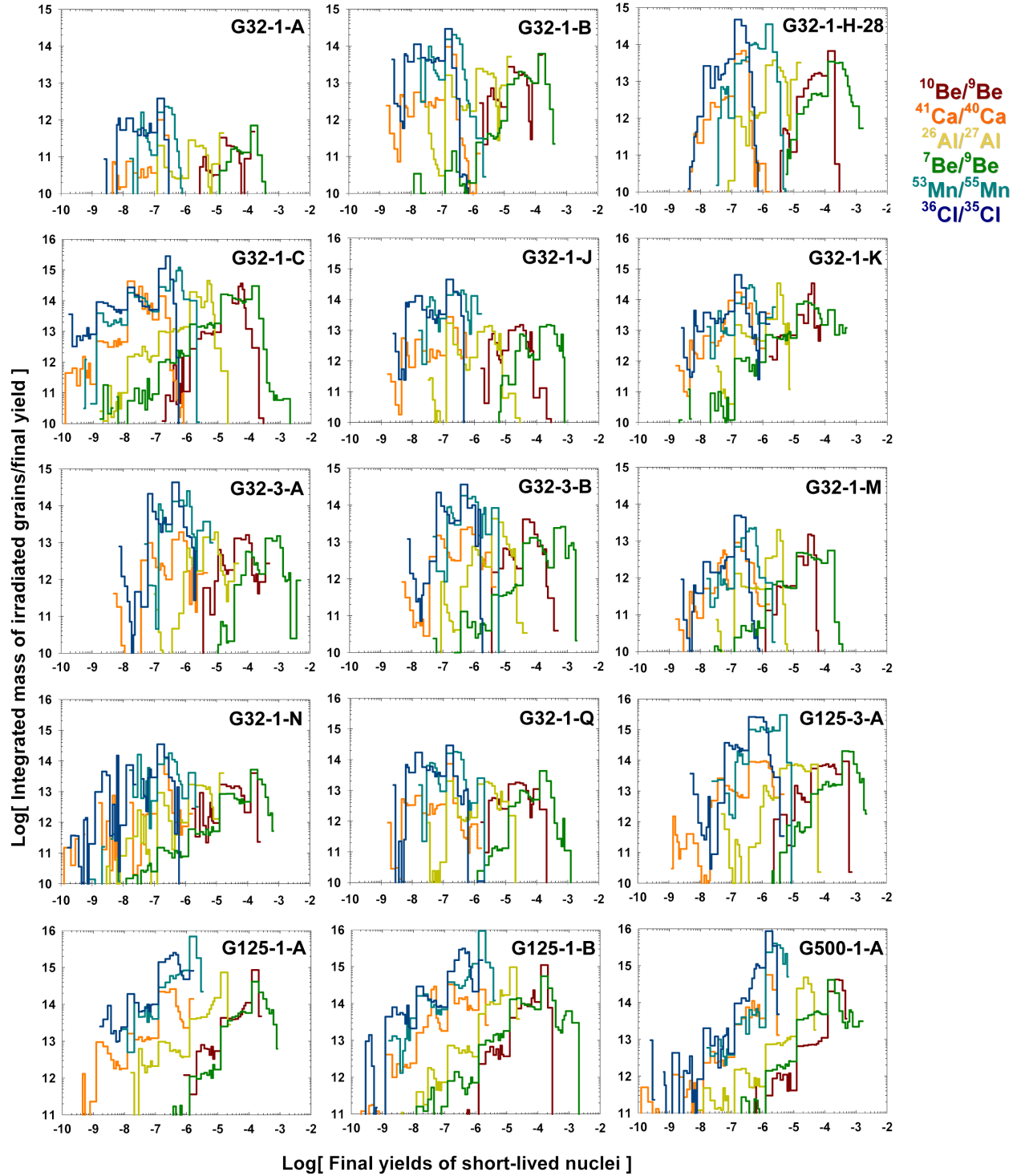


Fig. 3. The differential mass spectra of the final yields of the short-lived nuclides for the core-mantle ensemble of grains at the end of various simulations, and prior to the thermal processing by a hypothetical superflare. The mass of the grains is expressed in volumetric units (see text).

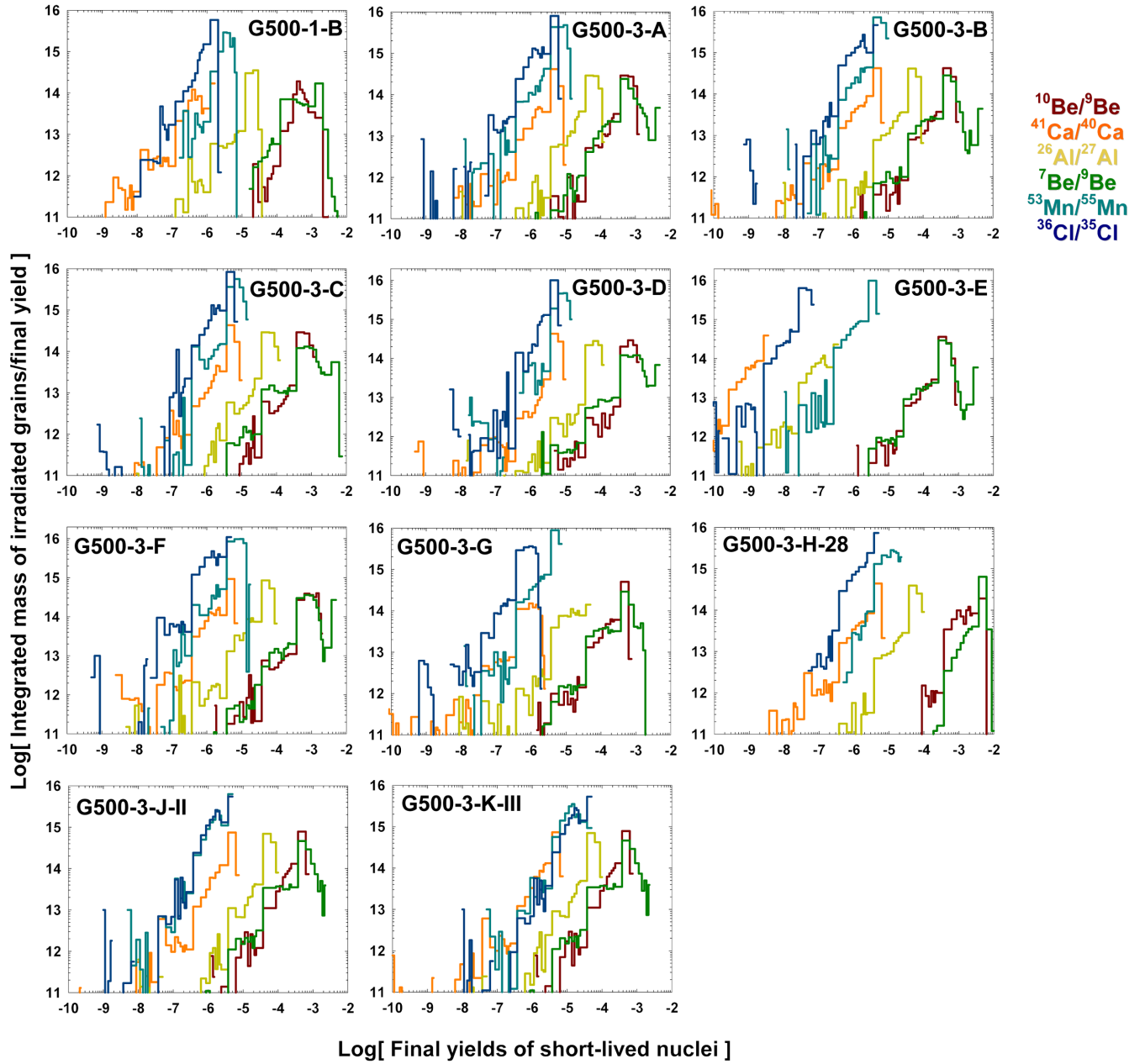


Fig. 3. *Continued.* The differential mass spectra of the final yields of the short-lived nuclides for the core-mantle ensemble of grains at the end of various simulations, and prior to the thermal processing by a hypothetical superflare. The mass of the grains is expressed in volumetric units (see text).

of $^{41}\text{Ca}/^{40}\text{Ca}$, $^7\text{Be}/^9\text{Be}$, $^{10}\text{Be}/^9\text{Be}$, and $^{26}\text{Al}/^{27}\text{Al}$ from that of $^{53}\text{Mn}/^{55}\text{Mn}$ and $^{36}\text{Cl}/^{35}\text{Cl}$ could be due to the distinct thermal evolutionary and irradiation history of the refractory cores and mantles. The average yields were found to be independent of a steady increase in the mass accretion rate by three orders of magnitude during five years of simulation runs.

In general, the low irradiation yields of the short-lived nuclides in G32 simulations result from the small residence time (~ 100 days) of the thermally processed and irradiated protoCAIs in the reconnection ring. Due to the steady supply of fresh grains into the reconnection ring, the thermally processed and irradiated protoCAIs homogenize quite frequently with the unprocessed grains. The mixing is more predominant in the G32-Lp3 ($Lp/Lx = 0.3$) simulations compared to the G32-Lp1 ($Lp/Lx = 0.1$) simulations, as the former simulations involve more rigorous thermal processing due to high ambient temperatures attained by the grains. In spite of the three-times-higher energetic particle fluence, the former infer irradiation yields of the short-lived nuclides that are comparable to the latter simulations. To produce the short-lived nuclides at their observed abundances, the irradiation contribution of an impulsive superflare corresponding to $Lx \sim 10^{34} \text{ ergs s}^{-1}$ lasting at least ~ 10 h and ~ 2 h would be essential for the G32-Lp1 and G32-Lp3 simulations, respectively.

The final average yields of the short-lived nuclides were found to be higher in the G125 and G500 simulations compared to the G32 simulations. Within an order of magnitude, the impulsive flare simulations can produce all the short-lived nuclides at their observed abundances. However, the production of the short-lived nuclides, specifically, ^7Be , ^{53}Mn , and ^{36}Cl in the G125-Lp1, G125-Lp3, and G500-Lp1 simulations would require an impulsive superflare irradiation contribution. The simulations G500-1-B-28, G500-3-H-28, and G500-3-I-28 that include $10^{27-28} \text{ ergs s}^{-1}$ X-ray flares' contributions infer comparatively higher yields of $^7\text{Be}/^9\text{Be}$, $^{10}\text{Be}/^9\text{Be}$, and $^{53}\text{Mn}/^{55}\text{Mn}$ even without superflare contributions. The yields of $^{41}\text{Ca}/^{40}\text{Ca}$ are high by two orders of magnitude compared to its experimental estimates. The high yields of the short-lived nuclides in the G125 and G500 simulations are due to the comparatively longer residence time of the protoCAIs in the reconnection ring compared to the G32 simulations. A longer residence time results in an adequate exposure of the protoCAIs to the energetic particles in the reconnection ring. Among the G125 and G500 simulations, the average yields of the short-lived nuclides remained almost constant over five years of simulation runs except for the G500 simulations where we observed a steady increase in the average yields by a factor of ~ 2 over five years.

The simulation G500-3-E with gradual flares can produce ^{10}Be alone. Inclusion of a gradual superflare irradiation for a couple of hours would be required to produce ^7Be , ^{41}Ca , and ^{53}Mn . The yields of $^{26}\text{Al}/^{27}\text{Al}$ and $^{36}\text{Cl}/^{35}\text{Cl}$ are

low even after the superflare contribution. The simulation G500-3-G, which includes both impulsive and gradual flares, produces all of the short-lived nuclides in proportions identical to those of the impulsive flare simulations. This simulation would require the contribution of a gradual superflare to produce all the short-lived nuclides. This scenario would be identical to the high fluence ratio of the GRD/IMP energetic particles recently studied by Leya et al. (2003).

Influence of the ProtoCAIs' Composition on Irradiation

Except for ^{36}Cl , no major difference exceeding an order of magnitude in the final average yields of the short-lived nuclides were observed due to the different compositions of protoCAIs (Table 5). The impulsive flare simulations G32-1-D-II and G32-1-E-III, corresponding to the model-II and model-III chemical compositions, respectively, were found to be almost identical to simulation G32-1-B with model-I chemical composition. There is, however, an order of magnitude increase in $^{36}\text{Cl}/^{35}\text{Cl}$ yields in simulation G32-1-E-III. This is due to the high S/Cl ratio of the model-III composition compared to model-I. The production of ^{36}Cl will be sensitive to the assumed S/Cl ratio. Identical results were found in simulations G500-3-B, G500-3-J-II, and G500-3-K-III.

Inferred Spreads in the Final Yields of the Short-Lived Nuclides

The differential mass spectra of the final yields of the short-lived nuclides exhibit significant spreads of almost two orders of magnitude in the final yields of the short-lived nuclides in the G32-Lp1 ($Lp/Lx = 0.1$) simulations (Fig. 3). No significant difference in the differential mass spectra was observed in simulations G32-1-B and G32-1-Q where the reconnection ring was divided into 5 and 10 annular rings, respectively. Even though there are certain resolvable features in the form of humps in some of the simulations, the humps are more prominent in the simulations with high coagulation fraction, e.g., G32-1-K, G32-1-L, and G32-1-M. The spreads in the final yields are confined within an order of magnitude in simulation G32-1-C. Apart from these simulations, the humps are not resolvable from the general average trends. The maximum spread in the yields is found for ^7Be , the shortest-lived nuclide. The spectra fall gradually towards lower yields on account of the decay of ^7Be along with its production. In the case of simulations that include $Lx \sim 10^{27-28} \text{ ergs s}^{-1}$ flares, e.g., G32-1-H-28 and G32-1-P-28, the spread in the yields of $^7\text{Be}/^9\text{Be}$ is confined within two orders of magnitude. For the simulation G32-1-N, where grain coagulation was not considered for the flares corresponding to $Lx \sim 10^{29-30} \text{ ergs s}^{-1}$, the spreads in the final yields are significantly large.

Compared to the G32-Lp1 simulations, the spreads in the G32-Lp3 ($Lp/Lx = 0.3$) simulations, e.g., G32-3-A and G32-3-B, are relatively small and confined to an order of magnitude. Due to higher ambient temperatures attained by the grains in

the G32-Lp3 simulations, the protoCAIs are more rigorously homogenized compared to the G32-Lp1 simulations.

The spreads in the differential mass spectra corresponding to the G125 and G500 simulations are relatively small compared to the G32 simulations. The essential spreads in the final irradiation yields are confined to an order of magnitude, and prominent features are observed in most of the G125-Lp1, G500-Lp1, and G500-Lp3 simulations. Within a factor of three, the humps in the impulsive flare simulations can explain the canonical value of 5×10^{-5} for $^{26}\text{Al}/^{27}\text{Al}$. The G500-Lp1 and G500-Lp3 simulations can also explain the experimentally observed $^{10}\text{Be}/^9\text{Be}$ ratios in CAIs. However, the yields of $^7\text{Be}/^9\text{Be}$, $^{53}\text{Mn}/^{55}\text{Mn}$, and $^{36}\text{Cl}/^{35}\text{Cl}$ are low and would require contributions from flares corresponding to $L_x \sim 10^{27-28} \text{ ergs s}^{-1}$ (see, e.g., the simulation G500-3-H-28).

The differential grain-size number distribution spectra for the G32-Lp1 simulations exhibit progressive wide spread in the mantle size distribution with the increase in the core size (Fig. 2). The number distribution peaks for $\sim 32 \mu\text{m}$ core (the smallest core size) and decreases with an increase in the core size. Simulation G32-1-B exhibits features at a mantle thickness of $50\text{--}60 \mu\text{m}$ for all the core sizes. This is compatible with the mantle thickness of $\sim 54 \mu\text{m}$ for the $32 \mu\text{m}$ core, estimated on the basis of the elemental constituents of the mantle and the core (Table 2). For the core sizes $> 32 \mu\text{m}$, there is an additional feature. This feature takes the form of a broad hump in the simulations with high numerical coagulation fraction, e.g., models G32-1-K, G32-1-L, and G32-1-M. The feature almost disappears in simulation G32-1-J with low coagulation. Almost identical trends were observed in the G32-Lp3, G125, and G500 simulations. Simulations G32-1-C and G125-1-B exhibit a wide range of mantle thickness for different core sizes. In these simulations, the thermally unprocessed grains were introduced into the reconnection ring as refractory cores (along with mantles) of different sizes, selected randomly.

Influence of the Recent Chandra Ultradeep Orion Project (COUP) Observations on the Simulations

The recent Chandra Ultradeep Orion Project (COUP) X-ray flare observations cover the most extensive high spatial resolution survey of YSOs for a long period of 13.2 days (Wolk et al. 2005). The X-ray properties of 28 solar-mass ONC stars were analyzed. The COUP data became available recently when this paper was already in the final review stage. The influence of some of the major features of the COUP observations on the present work can be estimated qualitatively. The criteria for identifying flares based on the COUP observations (Wolk et al. 2005) are distinct from the criteria used previously by Feigelson et al. (2001a). The X-ray activity of YSOs is merely accounted differently in the two works without missing any event. The COUP observations reveal 1–2 flares per week with $L_x = 10^{30-32} \text{ ergs s}^{-1}$ lasting 1 h

to 3 days for a sun-like YSO. These YSOs spend 70% of their time in a state characterized by weaker flares with $L_x \leq 10^{30} \text{ ergs s}^{-1}$ (Wolk et al. 2005). The power law energy distribution of the flare luminosities indicates that the weaker flares would be enormous (Flaccomio et al. 2005; Wolk et al. 2005). These flares would dominate the estimated energetic particle flux for the irradiation of protoCAIs. In the present work, we simulated 2 flares per week with $L_x = 10^{31-32} \text{ ergs s}^{-1}$ lasting 1–12 h (1–24 h, in a single case), almost identical to the COUP observations. However, the characteristic level of the COUP observations is difficult to model as the weaker flares cannot be distinctly identified. Even though the flares with $L_x = 10^{29-30} \text{ ergs s}^{-1}$ can be appropriately accounted using the previous observations of YSOs (Feigelson et al. 2001a), the flaring rate of flares with $L_x \leq 10^{28} \text{ ergs s}^{-1}$ can only be speculated, as has been done in some of the simulations. The final yields of the short-lived nuclides would be uncertain due to an inappropriate assessment of the irradiation contribution of these weaker flares.

DISCUSSION

Numerical simulations involving an elaborate framework of physico-chemical processes operating during the thermal evolution and the irradiation of protoCAIs in the magnetic reconnection ring have been completed. The simulations were based on the X-ray flare observations of YSOs. Although several assumptions have been made for numerical simplifications, a wide range of variations in the simulation parameters were used to explore the complexity of the thermal and the irradiation environment prevailing in the magnetic reconnection ring.

Dynamical Constraints on the X-Wind Irradiation Scenario

Within the present framework of assumptions, it is unlikely that the G32 simulations, with the grain-size distribution dominated by $32 \mu\text{m}$ size refractory cores, would result in an accumulation of protoCAIs in the reconnection ring. Among the three distinct grain size distributions with refractory cores in the range $32 \mu\text{m}$ – 20 mm (G32), $125 \mu\text{m}$ – 16 mm (G125), and $500 \mu\text{m}$ – 13 mm (G500), the latter two result in the accumulation of protoCAIs. This imposes stringent constraints on the thermal processing of protoCAIs in the reconnection ring (Shu et al. 2001) and the size of the typical refractory cores that condense subsequent to a strong flare (e.g., $L_x \geq 10^{31} \text{ ergs s}^{-1}$ for $L_p/L_x = 0.3$ models). The grains corresponding to these cores are the smallest and are predominant in a grain-size distribution (Fig. 2). The typical size of these refractory cores depends upon the average rock surface density Σ_r of the reconnection ring (Shu et al. 2001). In the X-wind irradiation scenario, as Σ_r steadily increases on account of protoCAIs accumulation

in the reconnection ring during the decades long X-wind cycle, the typical size of the smallest grain in the grain-size distribution increases. The constraint imposed by the G32 simulations imply that to result in a substantial accumulation of protoCAIs, the grain-size distribution should be dominated by the core-mantle assemblages $>100\ \mu\text{m}$. This would require an average rock surface density $\Sigma_r > 1.6\ \text{g cm}^{-3}$ at the beginning of the X-wind cycle to initiate substantial accumulation of protoCAIs.

With the accumulation of protoCAIs ($>100\ \mu\text{m}$) in the reconnection ring, Σ_r steadily increases. This results in an increase in the size of the typical refractory cores that condense subsequent to a strong flare. Due to the longer residence time of the grains corresponding to these refractory cores in the reconnection ring, the accumulation rate of the protoCAIs increases. This further results in an increase in Σ_r , and the entire cycle repeats in an iterative manner. In the present case, it is quite likely that the grain-size distribution corresponding to G125 will eventually evolve to that of G500. This will not only increase the average yields of the short-lived nuclides but would also narrow down the spreads in the final yields of the short-lived nuclides as inferred from the G125 and G500 simulations (Fig. 3). During the decades-long thermal processing, the protoCAIs may eventually evolve into refractory cores of sizes $\sim 500\ \mu\text{m}$ – $2\ \text{cm}$, with almost uniform ferromagnesian mantles as anticipated by Shu et al. (2001) and Gounelle et al. (2001). Due to our computational limitations it is not possible to evolve the grain-size distribution over the decades-long thermal processing of protoCAIs in the reconnection ring. Rather, the simulations G125 and G500 were run for short durations of five years to explore the sequential build-up and irradiation of protoCAIs in the reconnection ring.

Comparative Analysis of the X-Wind Irradiation Scenario with Stellar Nucleosynthesis

The production of ^7Be , ^{10}Be , ^{26}Al , ^{36}Cl , ^{41}Ca , and ^{53}Mn by the X-wind irradiation scenario is feasible only with an appropriate choice of simulation parameters (see, e.g., simulations G125 and G500). We have partially explored the parametric space in the present work. The critical parameters among these are the average rock surface density (Σ_r), variations during the X-wind cycle, the L_p/L_x ratio, the deduced flare areas, the inclusion of the weak flares corresponding to $L_x \leq 10^{28}\ \text{ergs s}^{-1}$, and the thermodynamical criteria for the condensation of grains and the coagulation of core-mantle assemblages. These various simulation parameters have to be fine-tuned to obtain the desirable yields of the short-lived nuclides. The physico-chemical processes involved in the thermal processing and irradiation of protoCAIs have to operate in a desired manner to render suitable yields of the short-lived nuclides.

It should also be mentioned that the various proposed stellar nucleosynthetic sources, e.g., Wolf-Rayet stars, supernova II, Ib/c, and AGB stars, also require fine-tuned stellar scenarios to explain the yields of the various short-lived nuclides in a self-consistent manner (Sahijpal and Soni 2006). Apart from the specific requirements of the dynamical factors associated with the injection and mixing of the short-lived nuclides into the presolar molecular cloud, the stellar yields of the short-lived nuclides are uncertain. The stellar yields are essentially model-dependent. Uncertainties in the yields could be due to uncertainties in the nuclear reaction rates, stellar mass-loss rates and the stellar physics of mostly nonrotating stellar models. Hence, the production of the short-lived nuclides either by irradiation or stellar nucleosynthesis requires suitable parameterization.

Comparison of the Simulation Results with the Empirical Abundances of the Short-Lived Nuclide

Some of the G500 simulations can explain the canonical abundance of the initial $^{26}\text{Al}/^{27}\text{Al}$. The experimental spread in the initial $^{26}\text{Al}/^{27}\text{Al}$ ratio for most of the CAIs exhibits a bimodal distribution (MacPherson et al. 1995). The higher initial $^{26}\text{Al}/^{27}\text{Al}$ in the distribution, centered on the “canonical” value of $\sim 5 \times 10^{-5}$, has a spread in the range of $(3\text{--}5.5) \times 10^{-5}$. The range could be further extended to the supracanonical value of $^{26}\text{Al}/^{27}\text{Al}$ (Young et al. 2005), thereby yielding a spread of a factor of two in $^{26}\text{Al}/^{27}\text{Al}$ ratio. The lower initial $^{26}\text{Al}/^{27}\text{Al}$, or the absence of ^{26}Al signature in some of the CAIs, is generally attributed to secondary thermal alterations of CAIs (MacPherson et al. 1995) or heterogeneity of ^{26}Al in the early solar system (see, e.g., Sahijpal and Soni 2006). The spread in the final yields of $^{26}\text{Al}/^{27}\text{Al}$ observed in some of the G500 impulsive flare simulations can explain the experimental spread around the canonical value.

Due to limited experimental data on ^{10}Be , the spread in the early solar system $^{10}\text{Be}/^9\text{Be}$ value is difficult to quantify. The experimental known spread of a factor of two in $^{10}\text{Be}/^9\text{Be}$ is compatible with the inferred spread in some of the G500 impulsive flare simulations. Due to limited experimental data on ^7Be , ^{36}Cl , and ^{53}Mn in CAIs, it is difficult to make a comparative analysis with the simulation results. However, in order to explain their early solar system abundances it would be essential to invoke flares corresponding to $L_x \leq 10^{28}\ \text{ergs s}^{-1}$ (see, e.g., simulations G500-3-H-28 and G500-3-I-28). Alternatively, the irradiation of protoCAIs by superflare(s) subsequent to their thermal processing in the reconnection ring would be required to explain the $^7\text{Be}/^9\text{Be}$, $^{36}\text{Cl}/^{35}\text{Cl}$, and $^{53}\text{Mn}/^{55}\text{Mn}$ ratios. The inferred $^{41}\text{Ca}/^{40}\text{Ca}$ ratio, however, is two orders of magnitude higher compared to its experimental value (Table 4). The possibility of a higher initial $^{41}\text{Ca}/^{40}\text{Ca}$ ratio in the early solar system cannot be ruled out.

The simulations in the present work were carried out by assuming two sets of values for $L_p(\geq 10 \text{ MeV/n})/L_x(0.5\text{--}8 \text{ keV})$, viz., 0.1 and 0.3. The uncertainties in the assessment of L_p/L_x have a substantial negative impact on the adopted thermal processing and the irradiation criteria. This could be further aggravated by the uncertainties in the flare areas. Compared to the Lp3 ($L_p/L_x = 0.3$) simulations, an increase in the L_p/L_x ratio, or a reduction in the assumed flare areas, will result in even higher ambient temperatures attained by the grains. This would result in a situation where the irradiation in the reconnection ring takes place while the grains are mostly in the vapor state. This scenario would be identical to the irradiation of a gas target, subsequently followed by the condensation of CAIs (Leya et al. 2003). However, in case the flare areas are increased, or the L_p/L_x ratio is reduced compared to the Lp1 ($L_p/L_x = 0.1$) simulations, the deduced ambient temperatures of the grains will be lower. This would result in comparatively less thermal processing of the grains. In an extreme scenario, the irradiation of an ensemble of thermally unprocessed grains at asteroidal distances has been carried out by Goswami et al. (2001). Subsequent to the irradiation, a superflare would be required to homogenize the inventories of the short-lived nuclides produced by irradiation.

The thermodynamical criteria involved in the condensation and the coagulation of core-mantle assemblages is highly debatable. A thorough feasibility assessment of the adopted thermodynamic criteria is extremely essential. In addition, it should be emphasized that even though there are meteoritic records of a few CAIs coated with thick chondrule mantles (see, e.g., Krot et al. 1999), these are exceptions rather than a general trend observed for CAIs and chondrules. In the present scenario, a significant amount of the ferromagnesian mantle has to be efficiently removed from the protoCAIs subsequent to their thermal processing and irradiation in the reconnection ring. This would probably take place by the direct exposure of the protoCAIs to the protosun's luminosity at the time of their launch by the X-wind (Shu et al. 2001). It is quite likely that the protoCAIs will significantly lose ^{36}Cl and ^{53}Mn to the protosun during the removal of the ferromagnesian mantle.

Constraints on the Luminosity and the Frequency of X-Ray Superflares

The crucial requirement of a superflare with $L_x = 10^{33\text{--}34} \text{ ergs s}^{-1}$ to produce all the short-lived nuclides has been realized in most of the simulations except for simulations G500-3-H-28 and G500-3-I-28, where the irradiation contributions of flares corresponding to $L_x \leq 10^{28} \text{ ergs s}^{-1}$ were included. In fact, the superflares with $L_x = 10^{33\text{--}34} \text{ ergs s}^{-1}$ alone can produce all the short-lived nuclides with a gas target of solar composition. CAIs with the canonical abundance of ^{26}Al can subsequently condense from the irradiated gas. However, so far the X-ray flares

corresponding to $L_x > 10^{32} \text{ ergs s}^{-1}$ have not been reliably observed, even during the most extensive observations of YSOs recently carried out by COUP (Favata et al. 2005; Wolk et al. 2005). The high intrinsic X-ray luminosity of $10^{33\text{--}34} \text{ ergs s}^{-1}$ of the flare observed by Grosso et al. (1997) was probably overestimated as no plausible magnetic loop can produce such strong X-ray emissions (Favata et al. 2005). Unlike the $10^{30\text{--}32} \text{ ergs s}^{-1}$ flares that are clearly enumerated and the $<10^{30} \text{ ergs s}^{-1}$ flares which are statistically inferred to be present (Wolk et al. 2005), the superflares corresponding to $L_x > 10^{32} \text{ ergs s}^{-1}$ have not been reliably observed. If these are real, they must be very rare. In the absence of these superflares, it would be difficult to generate the canonical value of $^{26}\text{Al}/^{27}\text{Al}$ by irradiation of protoCAIs except for the irradiation scenarios involving frequent flares corresponding to $L_x \leq 10^{28} \text{ ergs s}^{-1}$, e.g., simulations G500-3-H-28 and G500-3-I-28. Alternatively, a stellar origin of ^{26}Al would be essential to produce the canonical value in the early solar system (Sahijpal and Soni 2006).

Finally, it should be emphasized that the essential requirement for a "local" irradiation production is now entirely based on the widespread detection of ^7Be in the early solar system. The presence of ^{10}Be in the early solar system can be explained by the probable trapping of GCR ^{10}Be nuclei in the collapsing presolar molecular cloud core (Desch et al. 2004). Hence, it becomes essential to infer the widespread presence of ^7Be in the early solar system.

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