NUMERICAL SIMULATIONS OF THE PRODUCTION OF EXTINCT RADIONUCLIDES AND PROTO-CAIS BY MAGNETIC FLARING ASSOCIATED WITH PROTOSUN. S. Sahijpal and P. Soni, Department of Physics, Panjab University, Chandigarh, INDIA 160 014. (sandeep@pu.ac.in)

Introduction: X-ray flare observations of low mass protostars in the Orion nebula cluster obtained by *Chandra* X-ray satellite provides detailed characterization of magnetic flaring in protostars going through T Tauri phase [1]. Present work involves numerical simulations of irradiation production of extinct radionuclides, ^{41}Ca, ^{36}Cl, ^{26}Al, ^{10}Be and ^{53}Mn [2], and thermal processing of protoCAIs in the X-wind model formulation [3,4] using the X-ray flare observations [1].

Simulations: Magnetic reconnection ring with a width of 0.25 R_x, at a distance R_x~12 $R_\odot$ from the protosun's center was opted as the irradiation site [3]. Spherical dust grains with CI composition and radii (5µm–8mm) were uniformly introduced in the reconnection ring in Keplerian orbits modified by coronal plasma viscous drag [3]. The drag causes the grains to spiral inwards and finally accrete on protosun. This dynamical evolution was monitored throughout the thermal history of grains and their subsequent thermally processed generations. A steady fresh supply of grains with CI composition was maintained in order to replenish the grains lost to the protosun.

In order to model various flare characteristics for numerical simulations, recently obtained X-ray flare observations of Orion Nebula cluster obtained by *Chandra* X-ray satellite were used [1]. Two ½ day observations in the band 0.5–8 keV of 43 low mass protostars (0.7 – 1.4 $M_\odot$) with theoretical ages < 0.3 to 10 Myr showed strongly elevated and variable X-ray luminosities (Lx) in the range (10^{29}–$10^{31.5}$ ergs/s.) on timescales of 0.5–12 hours. Around 30 flares were identified over the exposure. The data set can be considered equivalent to 86 ½ day observations of a single solar mass protostar with one flare every 1.4 days [1]. Flares of different X-ray luminosities were clubbed together into four luminosities, viz., < log Lx (ergs/s.) > ~ 29, 30, 31, 32 (31.5 treated as 32) and a *flare luminosity frequency distribution* was obtained to simulate flares of different X-ray luminosities. Proton luminosities, Lp (≥ 10MeV/n) ~0.09 Lx were used in simulations [4]. Active flare areas were estimated by interpolating *approximate* flare areas of 1% and 100 % of the reconnection ring for Lx~10^{31}ergs/s and 10^{34}ergs/s., respectively. Ambient temperature attained by grains during flares was estimated using radiative balance criteria [3] and proton flux for different power law energy differential spectra (dN α $E^{-\gamma}$dE) were accessed using the corresponding flare area [5]. Deduced flare characteristics are presented in table 1.

Table 1. Flare characteristics for simulations.

Lx ergs/s	**Lp** ergs/s	**Number of flares**ϒ	**Temp.** (°K)	**Flare Area** (cm^2)	**Proton flux*** $cm^{-2}s.^{-1}$
10^{32}	9×10^{30}	33	≥2100	5×10^{22}	8×10^{12}
10^{31}	9×10^{29}	539	≥1725	1×10^{22}	4×10^{12}
10^{30}	9×10^{28}	1077	≥1420	2×10^{21}	2×10^{12}
10^{29}	9×10^{27}	176	≥1150	5×10^{20}	7×10^{11}

ϒ Number of flares in 5 years simulation run; * $\gamma = 4$, dN α $E^{-\gamma}$dE

The 0.25 R_x reconnection ring width was divided into five annular rings of widths 0.05 R_x. Flares were generated radially covering all the five annular regions. For a given flare, thermal reprocessing and mixing was treated independently for the five annular sections. Flare of a specific Lx, according to flare luminosity frequency distribution was generated randomly at a frequency of day at random coordinates with random time spans between 1-7 hours. The orbital motion of flare was synchronized with the reconnection ring plasma. Simulations were run for a period of 5-7 years with time step of *an hour*.

Simulations were initiated with a uniform distribution of grains with CI composition in the range (5µm–8 mm). The grain size distribution was covered by nine different sized grains having the radii relation of $2^{4/3}$ between two successive sized grains to numerically facilitate thermal coagulation of grains. Around 10^4 coordinates through out the reconnection ring were seeded with the full *flat* size distribution of grains numbering 10^{12} per size per coordinate. Thermal processing of grains involving evaporation and condensation were worked based on deduced flare characteristics using the condensation criteria for dust/gas =54×solar [6]. Ensembles of refractory cores (Ca-Al-rich) with ferro-magnesium mantles (Fe-Mg-Si-rich) were evolved for irradiation. Vapor was irradiated as 5µm grain for simplifications. All the proton, $^{3,4}He$ induced nuclear reactions with core-mantle grains, bare cores and vapor that can produce the radionuclides were considered [4,7]. $^3He/H$ ~0.3 & $^4He/H$ ~0.1 were considered for impulsive flares.

Flares corresponding to *Lx ~10^{32} ergs/s.* were considered to evaporate grains completely. Resulting vapors within flare area were thoroughly homogenized and irradiated. Subsequent to flare, refractory cores of radii 32 µm with composition; Ca(23%), Al(22%), O(46%), Mg(2.4%), Si(5.4%) & Be(630ppb) were condensed which were coated with uniform thickness of ferro-magnesium mantle of composition; Fe(23%), Mg(12%), Si(13%), O(46%), C(1.4%), Mn(0.08%), Cl(0.03%), S(2.2%), Cr(0.1%) & K(0.02%). Total inventory of Ca, Al, Be (including their radionuclides) was consumed in making cores with only 1/3 (CI composition) of volatiles C, S, Cr, K, Cl condensing in mantles. These cores and mantles constitutes 0.04 & 0.8 fraction of the CI composition, respectively, the remaining volatiles were removed from simulations. Mantles of 7µm–3cm thickness in 88 incremental steps of 10% thickness each were accessed each time based on ferro-magnesium inventory and the number of cores.

Flares corresponding to *Lx ~10^{31} ergs/s.* resulted in complete evaporation of mantles. Vapors were irradiated and complete homogenized. Bare cores (5µm–8 mm; in nine different discrete size steps) were irradiated and according to their sizes were homogenized to produce a single homogenized population size distribution. An hierarchical coagulation model whereby a fraction (PC31) of cores of a specific size coagulates to form cores of next bigger size was formulated. The last two *assumptions* are radical and have been invoked for simplification of otherwise tedious problem. Orbital history of grains at least for half year has to be inferred for that. Some variances of this model are being tried. Subsequent to the flare, ferro-magnesium mantle of uniform thickness was coated on all the bare cores using the criteria mentioned earlier.

Flares corresponding to *Lx ~10^{30} &10^{29} ergs/s.* were treated identically except for the energetic flux and flare area. The core-mantle assemblages were irradiated without any loss by evaporation. Two alternative models were tried for thermal processing. In model A, according to core sizes, the grains were homogenized to produce a single homogenized population size distribution. An hierarchical coagulation model whereby a fraction (PC30) of cores of a specific size coagulates to form cores of next bigger size was formulated. The mantles were accommodated according and subsequent to coagulation, a spherical core-mantle assemblage was obtained as inferred grain temperatures < 1700 ^{o}K [3]. In model B, the core-mantle assemblages were just irradiated with no thermal processing. This model completely avoids the two drastic assumptions involved in model A.

Results obtained for wide range of simulation parameters are presented in table 2. Average production of ^{26}Al, ^{10}Be, ^{53}Mn and ^{36}Cl was found to be correlated with 10× additional particle flux requirements for several models with γ~4 and ^{3}He/H~0.3. ^{41}Ca production was high in all these models. ^{10}Be & ^{53}Mn can be produced invariably in all the models with 10× additional flux requirements. Additional requirement of flux enhancement could be arranged by invoking flares with Lx >10^{32} & ≤10^{28} ergs/s, the later could be more common and is below the *Chandra's* detection limit [1]. Invariably in all the models, at least an order of magnitude spread in ^{26}Al/^{27}Al (identically for other radionuclides) was observed with no inferred canonical value or resolvable hump in the distribution. The inferred spread was found to be quite high in Model B where core-mantle grains were not thermally processed during flares corresponding to Lx ~10^{30} & 10^{29} ergs/s. The spread is essentially due to irradiation of different combinations of core-mantle configurations and was found to be independent of the variations in energetic particle flux received by grains. Variations in the energy power spectra (γ) was also studied by randomly generating flares corresponding to γ~3 & 4. The spread in ^{26}Al/^{27}Al was found to be two orders of magnitude. In all the models, frequent flares with Lx ~ 10^{34}ergs/s. would be essential to homogenize the spreads. In almost all the simulations, the production rates merged to the final spread within initial half year and thereafter remained same. Mass equivalent of the total mass introduced at the beginning of simulations was lost to the protosun during the initial two years.

Table 2. Average production of radionuclides along with the spread in the initial ^{26}Al/^{27}Al for different models. PC31 ~ 0.1

γ	Model	^{3}He/H *PC30*	^{10}Be/^{9}Be	^{41}Ca/^{40}Ca	^{26}Al/^{27}Al SPREAD	^{53}Mn/^{55}Mn	^{36}Cl/^{37}Cl
4	A	**0.3** ***0.1***	5×10^{-5}	3×10^{-7}	**5×10^{-6}** **10^{-6}–10^{-5}**	2×10^{-6}	6×10^{-7}
4	A	**0.3** ***0.4***	5×10^{-5}	2×10^{-7}	**4×10^{-6}** **10^{-6}–10^{-5}**	8×10^{-7}	2×10^{-7}
4	A	**0.3** ***0.7***	5×10^{-5}	2×10^{-7}	**4×10^{-6}** **10^{-6}–10^{-5}**	7×10^{-7}	2×10^{-7}
4	B	**0.3** ***0.0***	1×10^{-4}	4×10^{-6}	**1×10^{-5}** **10^{-8}–10^{-5}**	3×10^{-6}	1×10^{-6}
4	A	**0.0** ***0.4***	5×10^{-5}	1×10^{-9}	**8×10^{-8}** **10^{-8}–10^{-7}**	8×10^{-7}	2×10^{-7}
3	A	**0.3** ***0.4***	6×10^{-5}	6×10^{-8}	**7×10^{-7}** **10^{-7}–10^{-6}**	5×10^{-7}	5×10^{-8}
3&4	A	**0.3** ***0.4***	5×10^{-5}	2×10^{-7}	**3×10^{-6}** **10^{-7}–10^{-5}**	8×10^{-7}	2×10^{-7}

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REFERENCES: [1] Feigelson et al. (2002) *Ap.J.* **572**, 335. [2] Sahijpal (2003) *DAE-BRNS Symps. Nuclear Phys. BARC*, **46B**, 436. [3] Shu et al. (2001) *Ap.J.* **548**, 1029. [4] Lee et al. (1998) *Ap.J.* **506**, 898. [5] Gounelle et al. (2001) *Ap.J.* **548**, 1051. [6] Yoneda and Grossman (1995) *GCA*, **59**, 3413. [7] Goswami et al. (2001) *Ap.J.* **549**, 1151.