Energetic constraints on irradiation-induced production of Short-Lived Radionuclei in the early solar system

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Introduction: The recent report of refractory phases in cometary material [1] suggests that material processed at close distance from the nascent star has been widely spread over the accretion disc, supporting the x-wind model proposed by Shu et al. [2]. In the x-wind picture bare rocks could have endured an intense irradiation phase that could have contributed to the nucleosynthesis of at least some of the Short-Lived Radionuclei (SLR) whose decay products are observed in meteoritic material [3]. Deciphering the origin of SLR has profound implications on the solar system formation scenario and on the possibility to build an isotopic chronology of the first solids that condensated in the Early Solar System (ESS). The possibility to produce SLR by irradiation have been extensively discussed and challenged [3-7] in the last decade but most of these studies addressed the issue to *locally* produce the relative SLR abundance *ratios* within a given reservoir (gas and/or solids). Still, another crucial constraint is the *total amount* of nuclei that can be synthesized compared to meteoritic data. It is known that producing nuclei by nonthermal irradiation process is expensive in terms of energetics [8, 9]. The aim of the present work is to set a quantitative upper limit on the maximum amount of several SLR that can be obtained through interaction between accelerated particles emitted by the young Sun and the surrounding material.

Inputs of the calculations: We considered irradiation scenarios with accelerated particles having differential source energy spectra in power-law form, $dN/dE=KE^{-s}$ down to 1 MeV/A (i.e. below the threshold of nuclear reactions) and solar-flare composition with $^3He/\alpha$ ranging from 0 to 3 ($p/\alpha = 0.1$) [10]. We considered both chondritic solid target chemistry and gas target of solar composition [11] and computed the energy losses using the TRIM code [12]. We studied all p, α and ^3He-induced reaction channels leading to ^{10}Be, ^{26}Al, ^{53}Mn, ^{36}Cl, and ^{41}Ca. We used experimental data when available or we computed theoretical excitation functions using a nuclear reaction code (TALYS) [13]. In order to maximize the production we considered a thick target limit [8]. Figure 1a shows calculated yields for ^{26}Al and ^{10}Be production, expressed as the numbers of synthesized atoms per erg of total kinetic energy contained in the accelerated particles. The recent Chandra Orion Ultradeep Project (COUP) dataset on Young Stellar Object (YSO) [14] provides constraints on X-ray luminosity for young stellar analogs of our Sun (L_X in the range 10^{30}-10^{31} erg s^{-1} [15]). Taking a particle-to-X-ray luminosity ratio similar to the one reported in modern Sun impulsive flares, $L_p(E>10\ MeV)/L_X\sim0.09$ [3, 16], and a typical integration time of 1 Myr, one obtains a total kinetic energy available for accelerated protons (E>10 MeV) of $\sim10^{43}$ erg which allows to predict from the thick-target yields the maximum numbers of SLR that can be synthesized by irradiation. We report in figure 1b the total mass of rocks that can be obtained when irradiation-produced SLR are mixed with a chondritic reservoir [11], assuming they exhibit the canonical SLR abundance ratios deduced from meteoritic data (values from [17]).

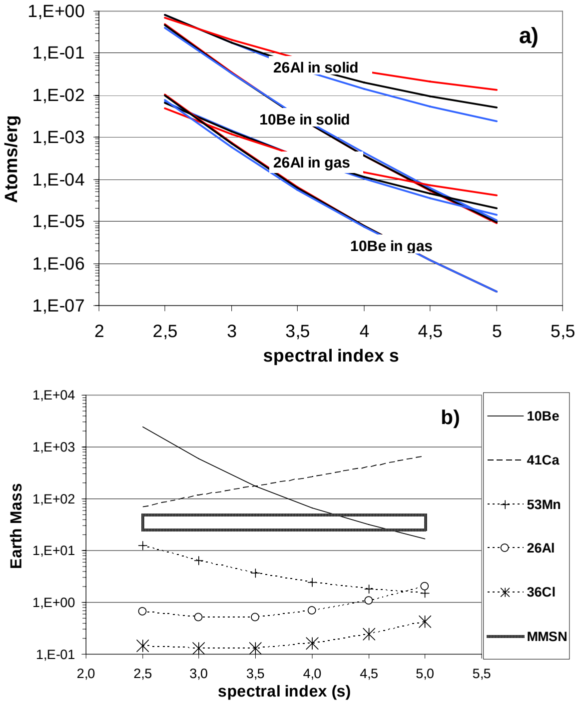

Figure 1: a) Maximum production yields for ^{10}Be and ^{26}Al in a thick target limit in both solid and gas targets, as a function of accelerated particle spectral index (blue line : no ^3He, black line : $^3He/\alpha=0.5$, red line : $^3He/\alpha=3$). b) The maximum mass (in Earth mass units) of chondritic material bearing irradiation-induced SLR at their canonical abundance value. Irradiation conditions: solid target, $^3He/\alpha=1$. MMSN : Minimum Mass Solar Nebula.

Discussion: Evidence for SLR decay has been demonstrated in numerous mineral phases of primitive solar system materials [18] and it is generally assumed that CAI and chondrules formed from an homogenous reservoir, such that the differences observed between their inferred abundance ratios can be interpreted in terms of isotopic decay. The Minimum Mass Solar Nebula (MMSN) that is necessary to build the planets corresponds to a disk (gaz+solids) of 1-2% of the Sun mass [19] leading to a MMSN of 25-50 Earth Mass ($M_\oplus$) of rocky material. From figure 1b it is clear that the maximum amounts of material containing irradiation-produced ^{26}Al, ^{53}Mn, and ^{36}Cl falls, for most irradiation scenarios, below 10 $M_\oplus$. By contrast, large reservoirs containing ^{10}Be and ^{41}Ca can be obtained trough irradiation. The reservoirs obtained for the irradiation of solar gas target fall 2 orders of magnitude below the ones indicated in figure 1b. If the SLR were homogenously distributed over the MMSN two firm conclusions can be drawn: i) irradiation of a solar gas target can produce only ^{10}Be at a level compatible with the MMSN for hard spectra (s=2.5) ; ii) irradiation of solids can only account for ^{10}Be and ^{41}Ca and the other SLR require another explanation.

If one assumes an heterogeneous distribution of SLR in the ESS, taking a reduced ^{26}Al/^{27}Al ratio of 10^{-5} in chondrules [20] compared to the canonical value measured in CAIs (5×10^{-5}) enhances by a factor 5 the ^{26}Al-related reservoir in figure 1b and then only in an extreme irradiation scenario (s=5, ^{3}He/$\alpha = 3$) one can reach an amount of 25 $M_\oplus$ (the lower MMSN limit). But this extreme case raises several critical difficulties. Large amounts of ^{26}Al are produced in the s=5 case because the integration of the cross sections down to their nuclear threshold implicitly assumes that a tremendous amount of the star energy is converted into high energy particles acceleration. Still, in impulsive flares most of the nonthermal energy is contained in accelerated particles of energies below 1 MeV/A [21] and the required total particle energy (for s=5 case) should thus be > 10^{47} erg, a non-realistic value compared to the total gravitational energy available in the star (~10^{48} erg). A second major difficulty in this extreme case is the high particle fluence received by the irradiated objects: taking a protons flux (E>10MeV) of 2×10^{10} cm^{-2} s^{-1} [5, 6] one obtains in this extreme case a minimal average power deposition of 250 W cm^{-2} (with potential orders of magnitude variations during the flares). Under such conditions the solids should melt (and evaporate) and the optimal solid thick target limit does not seem possible even in the short duration of the flares (3 h – 3 days) [14].

From a more general point of view, the ^{26}Al canonical value for CAIs in itself raises an issue. Indeed, if CAIs are formed and transported to asteroïdal distances in an early embedded phase of the star [2] they have to get mixed with a large amount of accreting material (still representing 20–50% of the Sun's mass). In the x-wind picture a mass greater by a factor up to 100 of these rocky solids must have existed in the disk before being accreted by the star [2]. The narrow time range of a few hundred thousand years for the formation of CAI [17] is in agreement with the typical duration of the embedded protostar phase. If CAIs are indeed "sprayed over the entire solar system" [2], then in a 0.1 $M_\odot$ disk one needs 6×10^{45} atoms of ^{26}Al to reach the canonical value *only in* CAI. Assuming a typical time of 0.2 Myr for the embedded phase [2], in the best (probably non-realistic) case we obtain a maximum of 6×10^{43} atoms of ^{26}Al. Provided that one finds a way to efficiently trap the CAIs and/or make them in later phases of the ESS it seems that the bulk of the ^{26}Al contained in CAIs cannot be produced by irradiation.

Finally it should not be concluded from figure 1b that the high mass values in ^{10}Be and ^{41}Ca indicate an overproduction of these nuclei in irradiation scenarios. Many physical processes can lead to orders of magnitude reduction in these upper limits and a large part of these nuclei can have ended their lives prematurely in the building star. Concerning ^{10}Be the thick target limit is only reached for large objects (d>10 cm) due to the high-energy thresholds of the relevant cross sections and irradiation of smaller objects leads to a strong reduction of the ^{10}Be production (up to a factor of 100 for 0.01 cm grains) due to the escape of the high-energy incident particles from the grain. The ^{41}Ca yield is extremely sensitive to several input parameters such as the ^{3}He/α ratio and the spectral energy cutoff at low energy, and a reduction of this yield by up to a factor of 100 is within the uncertainties on these parameters. We will present detailed calculations of the yields of SLR of interest showing their dependence on various irradiation scenarios and finite size of the irradiated objects.

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