Irradiation production of the short-lived nuclides ^{10}Be and ^{36}Cl by the early active sun

S. Sahijpal
Department of Physics, Panjab University, Chandigarh – 160014, INDIA
email: sandeep@pu.ac.in

Introduction

Our solar system originated around 4.56 billion years ago [1]. The sun and the planetary system formed from the gravitational collapse of an interstellar molecular cloud. Some of the pristine meteoritic samples that are essentially derived from asteroids provide substantial information regarding the physico-chemical processes that shaped our solar system. These samples infer the presence of some short-lived nuclides that were present in the early solar system [1-5]. The presence of these short-lived nuclides, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{10}Be, ^{60}Fe and ^{53}Mn ($\tau < 10$ million years) in the early solar system has been a puzzling issue in terms of the origin of these nuclides and the associated astrophysical interpretation(s) [1-5]. While ^{10}Be and ^{60}Fe are considered to be definitely of the irradiation [2-4] and the stellar nucleosynthetic origins [5], respectively, the exact source of the remaining short-lived nuclides is still uncertain [1-5].

The irradiation scenario involves the irradiation of the early solar system gas and dust by energetic particles (1-1000 MeV/n) from the early active sun going through the T Tauri phase [2-4]. ^{10}Be definitely was produced by the irradiation scenario along with some of the other short-lived nuclides. The stellar nucleosynthetic scenario involves the origin of the short-lived nuclides, e.g., ^{60}Fe by a star just prior to the initiation of the formation of the solar system. In the present work, I make an assessment to understand the irradiation origin of the two short-lived nuclides, ^{10}Be and ^{36}Cl.

^{10}Be and ^{36}Cl in the early solar system

The presence of ^{10}Be and ^{36}Cl in the early solar system necessitates the need of irradiation in the vicinity of the protosun going through T Tauri phase as the estimated abundances of these nuclides cannot be produced by stellar nucleosynthesis. Recently, there have been several developments in the abundance determination of these short-lived nuclides in the early solar system phases. Higher values of $>10^{-2}$ and 10^{-5} have been observed for ^{10}Be/^{9}Be and ^{36}Cl/^{35}Cl, respectively, in meteoritic phases [4,7]. The empirical cross-section rates have also been determined for some of these nuclides from the spallation reactions [4,7]. I have made assessment of the yields of these radionuclides that are definitely known to have been produced by irradiation [3] within the X-wind irradiation scenario [6].

The irradiation scenario

Numerical simulations were performed to make assessment in the spreads of the yields of ^{10}Be and ^{36}Cl subsequent to decade long irradiation [2,3] near the protosun going through the T Tauri phase [6]. The irradiation production of the two radionuclides was analyzed in context with the production rate of ^{26}Al. This was done to ensure that ^{26}Al is of stellar origin, with less than 10% contribution from irradiation [3]. Around thirty-five energetic proton, ^{3}He and ^{4}He induced spallation nuclear reactions with the stable isotopes of C, N, O, Na, Mg, Al, Si, Cl, K, S, Fe and Ni were considered in the energy range 1-1000 MeV/N for the production of ^{10}Be, ^{26}Al and ^{36}Cl. The theoretical reactions rates were considered in the absence of experimental available reaction cross-sections. Some of the recent available cross-sections were also used [4,7]. The gradual (proton & ^{4}He rich) flares with the X-ray luminosity (Lx) in the range 10^{29-32} ergs s^{-1} were numerically triggered based on the empirical data derived from X-ray flares of the young stellar objects [8]. ^{3}He rich impulsive flares were also triggered in some of the simulations. The normalized production rates of the short-lived nuclides ^{10}Be and ^{36}Cl after a decade long irradiation of early solar grains corresponding to distinct nature of flares are presented in fig. 1. I ran four simulations with gradual flares. Among these simulations, three were run with additional possibilities of i) low intense flares with Lx < 10^{29} ergs s^{-1}, ii) a spike of impulsive flare with Lx ~ 10^{34} ergs s^{-1} and iii) an equal contributions of impulsive flares. The higher values of >10^{-2} and 10^{-5} for the observed $^{10}Be/^{9}Be$ and $^{36}Cl/^{35}Cl$, respectively, in the early solar system would require stringent conditions regarding the nature of the protosolar flares. A substantial contribution of impulsive flares would be required. This has to be achieved without substantial irradiation contribution of ^{26}Al [3].

Acknowledgements: This work is supported by PLANEX (ISRO) research grant.

References

[1] G. J. Wasserburg, et al. Nuclear Physics A, **777**, 5 (2006).
[2] S. Sahijpal, In DAE-BRNS Symp. Nuclear Phys., 436 (2003).
[3] S. Sahijpal & G. Gupta, Meteoritics & Planet. Sci. **44**, 879 (2009).
[4] G. F. Herzog, et al. Meteoritics & Planet. Sci. **46**, 1427 (2011).
[5] A. G. W. Cameron et al. Astrophys. J., **447**, 53 (1995).
[6] F. H. Shu et al. Science **277**, 1475 (1997).
[7] M. Bowers, 44th Lunar & Planet. Sci. Conf., NASA, Ab. #2543 (2013).
[8] E. D. Feigelson et al., Astrophys. J., **572**, 335 (2002).

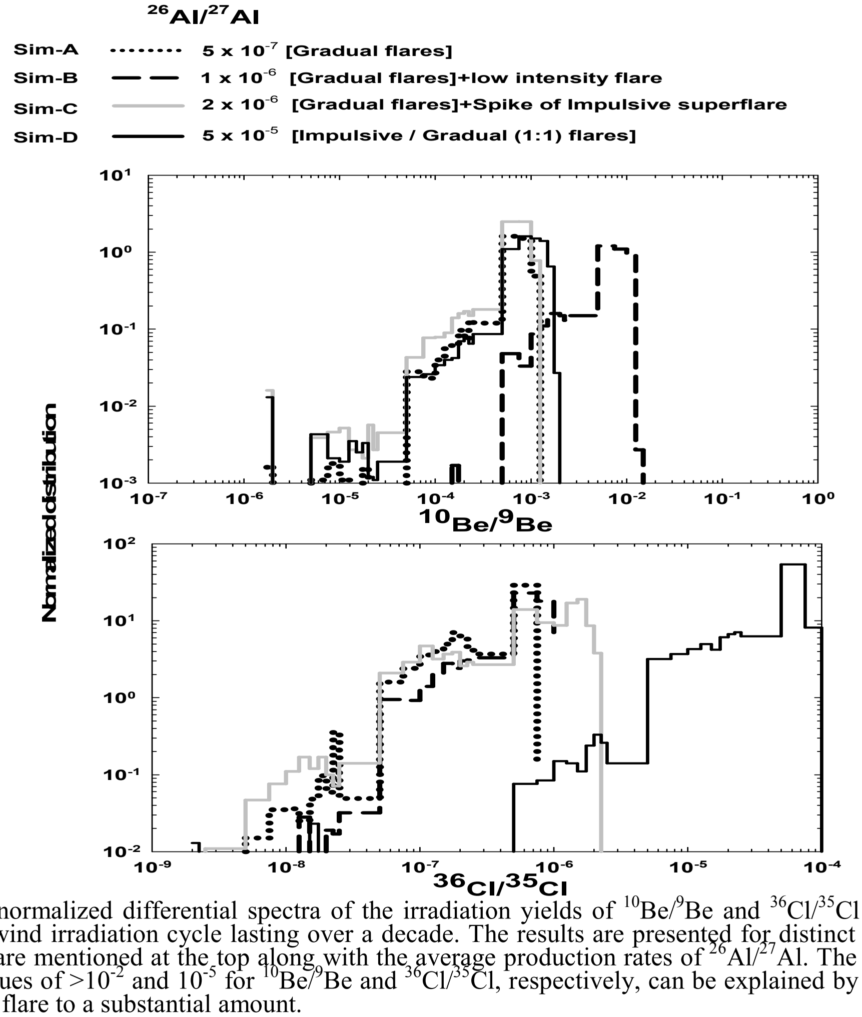

Fig. 1 Renormalized differential spectra of the irradiation yields of $^{10}Be/^{9}Be$ and $^{36}Cl/^{35}Cl$ during a single X-wind irradiation cycle lasting over a decade. The results are presented for distinct nature of flare that are mentioned at the top along with the average production rates of $^{26}Al/^{27}Al$. The observed higher values of >10^{-2} and 10^{-5} for $^{10}Be/^{9}Be$ and $^{36}Cl/^{35}Cl$, respectively, can be explained by invoking impulsive flare to a substantial amount.