CONTRIBUTIONS OF SHORT-LIVED NUCLIDES BY WOLF-RAYET STARS AND SUPERNOVAE 1b/c TO THE EARLY SOLAR SYSTEM.

S. Sahijpal and P. Soni, Dept. of Physics, Panjab University, Chandigarh, India 160 014. (sandeep@pu.ac.in)

Introduction: Wide range of stellar [1,2] as well as irradiation [3,4,5] nucleosynthetic scenarios have been proposed to understand the presence of several short-lived nuclides ($\tau \leq$ 5Ma) in the early solar system. In order to infer their most plausible source(s) and the extent of distribution in the nebula, detailed isotopic and dynamical constraints have to be worked out for all possible scenarios. In an ongoing effort to impose isotopic constraints on the various stellar nucleosynthetic sources [6,7], an attempt is made here to access the role of a single massive (60M⊙) Wolf-Rayet (WR) star and supernovae type 1b/c (SN1b/c). We have also attempted a detailed study of a single massive 60M⊙ WR star evolved through SN1b/c [2].

Nucleosynthetic models: Single massive stars ($\geq$ 40 M⊙), and relatively less massive stars in close binary systems are considered to be progenitor of SN1b/c [2,8]. Former looses their H & He envelops during WR phase and can finally evolve through SN1b/c [8,9,10]. However, in close binary systems depending upon the mass of the evolving primary star, large-mass He stars probably evolve through WR phase [8,11], whereas, relatively small-mass He stars loose their He envelope to their binary [8]. Both the evolutionary tracks finally lead to CO core formation, the progenitor of SN1b/c. In the present work, ejected nucleosynthetic yields of *exclusively* SN1b/c of large-mass (SNLM), 10, 20 M⊙ He stars [11], and yields of relatively small-mass (SNHe), 6, 8 M⊙ He stars evolved through SN1b/c with $E_{expl.}(10^{51}$ ergs) [12] were considered. Remaining nucleosynthetic models [11,12] corresponding to different masses and $E_{expl.}(\geq 10^{51}$ ergs) were also studied.

Nucleosynthetic yields for single massive, non-rotating (W60NR) as well as rotating (W60R) stellar models of 60 M⊙(Z⊙) WR star were obtained from mean enhancement factors of various nuclides [13]. These yields are based on the recently revised mass-loss rates that take into account the WR wind clumping effects [9,14]. Ejected yields of *non-decayed* ^{26}Al [14] obtained by the same group with identical models were used that are lower then those obtained without including WR wind clumping effects [14,15].

In addition to the above non-exploding WR 60 M⊙ stellar models, a case of single *non-rotating* 60 M⊙ star evolved through SN1b/c was also studied. Two models dealing with the complete nucleosynthetic evolution of short-lived and *major* stable isotopes were synthesized corresponding to different mass-loss evolutionary details [14,15]. Model (WSNA) was synthesized using the recently revised mass-loss rates that take into account WR wind clumping effects [14]. Nucleosynthetic yields from W60NR model were taken for the WR phase. WSNA will loose ~14 M⊙ [13] during complete WR phase and will be finally left with a star of ~11 M⊙ CO core [14]. In the absence of any suitable evolutionary model for ~11 M⊙ CO core, we adopted SN1b/c model (CO138E1) of a 13.8 M⊙ CO star for only the *major* stable isotopes [16]. Short-lived nuclides yields were taken from SN1b/c [12] of a 16 M⊙ He star (10^{51}ergs), as their production essentially takes place in their final 13.8 M⊙ CO core collapse. Comparative analysis of W60NR model combined appropriately with 16 & 10 M⊙ He stars [12] that evolve to ~13.8 & 8 M⊙ CO cores, respectively, suggests that choice of 13.8 for 11 M⊙ CO will not have large alterations in inferred stable isotopic effects, whereas, short-lived nuclides will be effected by a factor up to 2. Another model (WSNB) was synthesized based on previously used mass-loss rates (*uncorrected* wind clumping effects). In this model, a single 60 M⊙ star will evolve to a ~23 M⊙ mass-losing He star [11] and will finally undergo SN1b/c as a result of ~4.3 M⊙ core collapse [11]. Yields for the pre-supernova evolution of 23 M⊙ mass-losing He star were obtained by extrapolating the nucleosynthetic yields of 10, 15, 20 M⊙ mass-losing He stars [11]. ^{26}Al yield was taken from WR model for previously used mass-loss rates [15]. In the absence of any suitable model for the final core collapse of ~4.3 M⊙, we adopted the SNIb/c model of 3.6 M⊙ core collapse that corresponds to initial 20 M⊙ mass-losing He star [11]. This will result in underestimating the production of several major stable and radionuclides. ^{26}Al yield of WR+SN1b/c in all will not be affected by more than a factor of 2 as most of it will be ejected during WN stage [10]. Average time span of 0.4 Ma was assumed between the ejection of ^{26}Al during WN and SN1b/c [13,14] for both models, and was incorporated in short-lived nuclides yields.

Role of SN II [6,17] $\leq$ 25 M⊙ was re-accessed in view of improvements in stellar theories that incorporate stellar mass-loss rates and other refinements [18].

Identical methodology for various stellar models [6,7], was adopted to infer associated isotopic effects (stable and short-lived nuclides) to obtain the canonical value of ^{26}Al/^{27}Al in CAIs [19] after a dilution factor (D) and free decay time interval (Δ; t = 0 at the ejection of ^{26}Al during WN phase in WR models).

Results and Discussions: Normalized isotopic ratios of short-lived nuclides and percentage enhancement factor inferred in the abundance of stable isotopes for a representative set of nucleosynthetic models are presented in Table 1. Except for the case of SNHe-6 & 8 M⊙, all nucleosynthetic models infer large stable isotopic effects, specifically in the core He-burning products (^{12}C & ^{22}Ne) for WR models.

***SNLM*:** Even for Δ ~0.8 Ma, all these SNIb/c models [11] exhibit large stable isotopic effects. Production of ^{53}Mn & ^{60}Fe is up by two orders of magnitude, whereas, ^{36}Cl & ^{41}Ca are produced in proportions.

SNHe: Among all the stellar sources [6,7] including presently studied, SNHe-6 & 8 M⊙ models [12] have large ^{26}Al yields as a result these models with $E_{expl.}(1\text{-}30)\times10^{51}$ ergs, exhibit extremely small ($\leq\varepsilon$) stable isotopic effects for Δ ~0.8 Ma with large inferred dilutions ($D \sim 10^{5-6}$). However these models barely produce ^{53}Mn (produced as ^{53}Fe), with orders of magnitude low ^{36}Cl, ^{41}Ca & ^{60}Fe. Δ can be easily relaxed to couple of million years without incorporating any stable isotopic effects. ^{26}Al & ^{53}Mn, alone will be produced by these stellar sources (at inferred distances > 20 pc [2]) with the remaining short-lived nuclides from irradiation production scenarios [3,4,5].

W60NR & W60R: Both these non-exploding WF models exhibit enrichments in the major He-core burning products even for Δ ~0.8 Ma. These models can produce ^{36}Cl & ^{41}Ca (to an extent) alone. W60R model that incorporates stellar rotation yield considerably lower stable enrichment factors as a result of increase in ^{26}Al production [14]. Further improvements in the stellar nucleosynthetic theories for rotating stellar models to enhance ^{26}Al production by a factor of 2 has been proposed recently to explain γ-ray line intensity and ionizing luminosity in the Cygnus region [14] although the detailed nucleosynthetic yields have not been revised. These improvements in ^{26}Al yield will effect WR models, specifically WSNA-B, as some of the later models can produce ^{60}Fe.

WSNA & WSNB: These diverse synthesized (non-rotating) models dealing with different stellar wind mass-loss rates exhibit enrichments in both He-core burning products and CO- core collapse products. Enrichments of He-core burning products can be reduced to an extent by invoking rotating stellar models as discussed above. Enhancements in CO-core collapse products in the model WSNB are relatively small compared to WSNA probably due to relatively small mass of progenitor CO-core. Incorporation of stellar rotating model would not only increase ^{26}Al production but will also result in relatively small CO-core for WSNA model. Among the two models, WSNB produce all the mentioned short-lived nuclides. Production of ^{60}Fe in WSNA model needs further examination.

Table 1. Normalized isotopic ratios for short-lived nuclides and percentage enrichment of some stable isotopes at the time of CAI formation. $[^{26}Al/^{27}Al]_{norm} = 1$

	SNHe 8E1	**SNLM 20**	**W60NR**	**W60R**	**WSNA**	**WSNB**	**S25** [18]
Δ (Ma)	0.8	0.8	0.8	0.8	1.2	1.2	0.8
^{36}Cl/^{35}Cl	2E-2	9E+0	3E+0		1E+1	3E+0	3E+1
^{41}Ca/^{40}Ca	5E-3	3E+0	3E-1		7E+0	9E-1	2E+1
^{53}Mn/^{55}Mn	6E-1	2E+2			3E+2	5E+1	4E+2
^{60}Fe/^{56}Fe	2E-10	1E+2	1E-4		1E-4	3E+1	1E+2
^{12}C	0.0	2.7	~5	1.6	4.5	5	1.3
^{16}O	0.0	1.0	~1	0.1	~6	0.4	3.3
^{22}Ne	0.0	1.8	7.4	3.7	~6	~9	2.0
^{24}Mg	0.0	1.2	0.1	0.2	~4	0.4	2.7
^{28}Si	0.0	2.0	0.1	0.3	~4	0.6	5.2
^{32}S	0.0	1.1	0.1		~2	0.3	3.5
^{40}Ca	0.0	0.8	0.1		2	0.3	2.7

Adopted ratios at the time of formation of CAIs
^{36}Cl/^{35}Cl = 1.4×10^{-6}, ^{41}Ca/^{40}Ca= 1.5×10^{-8}, ^{53}Mn/^{55}Mn = 6×10^{-6}
^{60}Fe/^{56}Fe = 3e-fold (4×10^{-9} - Chervony Kut) [6]

Invariably, almost all the stellar sources considered in the present and previous studies [6,7], except for few e.g., SNHe-6 & 8 M⊙ models, infer substantially wide ranging stable isotopic effects. Even after considering uncertainties in nucleosynthetic yields (*only* to an extent), the resulting stable isotopic effects, specifically in major CAI forming elements (e.g., O, Ca, Ti, Mg, Si, etc.) could have been clearly identified among CAIs from (PLACs & SHIBs) CM, CV, CH, etc., chondrites, some of which have contrasting $(^{26}Al/^{27}Al)_{ini.}$. In addition, substantial enrichments of certain isotopes, e.g., ^{12}C, ^{22}Ne, etc., could have repercussions on GCE.

***Acknowledgements*.** This work was supported by ISRO (PLANEX) grant. We are thankful to IUCAA's associateship programme.

References: [1] Goswami & Vanhala (2000) *Protostars & Planets IV*, 963. [2] Cameron et al. (1995) *Ap.J.* **447**, L53. [3] Leya et al. (2002) *LPSC XXXIII*, Abstract #1268. [4] Gounelle et al. (2001) *Ap.J.* **548**, 1051. [5] Goswami et al. (2001) *Ap.J.* **549**, 1151. [6] Sahijpal (2002) *LPSC XXXIII*, Abstract #1095. [7] Sahijpal (2002) *MAPS* 65, Abstract #5071. [8] Nomoto et al. (2001) Supernova & Gamma ray bursts. *Space Tele. Sci. Symp. Ser.* **13**, **Cambridge Univ. Press** 144. [9] Heger et al. astro-ph/0211062. [10] Cerviño et al. (2000) *A&A* **363**, 970. [11] Woosley et al. (1995) *Ap.J.* **448**, 315. [12] Nakamura et al. (2001) *Ap.J.* **555**, 880. [13] Meynet et al. (2001) *Space Sci. Rev.* **99**, 73. [14] Knödlseder et al. (2002) *A&A* **390**, 945. [15] Meynet et al. (1997) *A&A* **320**, 460. [16] Nakamura et al. (2001) *Ap.J.* **550**, 991. [17] Wasserburg et al. (1998) *Ap.J.* **500**, L189. [18] Rauscher et al. (2002) *Ap.J.* **576**, 323. [19] MacPherson et al. (1995) *Meteoritics* **30**, 365.