TRIGGERED STAR FORMATION AT THE PERIPHERY OF THE SHELL OF A WOLF-RAYET BUBBLE AS THE ORIGIN OF THE SOLAR SYSTEM V. V Dwarkadas[1], N. Dauphas[2], B. Meyer[3], P. Boyajian[1] and M. Bojazi[3], [1]Dept. of Astronomy and Astrophysics, University of Chicago, 5640 S Ellis Ave, ERC 569, Chicago, IL 60637 (vikram@oddjob.uchicago.edu), [2]Origins Lab, Department of the Geophysical Sciences and Enrico Fermi Institute, University of Chicago, [3]Dept. of Physics and Astronomy, Clemson University, Clemson, SC.

Introduction: A critical constraint on solar system formation is the high $^{26}Al/^{27}Al$ abundance ratio of 5×10^{-5} at the time of formation, which was about 17 times higher than the average Galactic ratio [1,2,3,4]. The $^{60}Fe/^{56}Fe$ value measured from meteorites is about 2×10^{-8}, at least an order of magnitude lower than the Galactic background [4,5]. The abundance of ^{26}Al as inferred in meteorites is too high [4,6,7] to be accounted for by long-term Galactic chemical evolution [4,8,9] or early solar system particle irradiation [10,11]. This challenges the assumption that a nearby supernova (SN) was responsible for the injection of these short-lived radionuclides into the early solar system [12], unless one can explain why a SN injected only ^{26}Al and not ^{60}Fe.

Sources of ^{26}Al include SNe, AGB stars, and Wolf-Rayet (W-R) stars. The probability of an AGB star being found near the Sun is extremely small [13], and it is unlikely to simultaneously explain the initial solar system abundance of ^{26}Al, ^{60}Fe, ^{107}Pd and ^{182}Hf [14].

Wolf-Rayet Stars: This suggests W-R stars as the ^{26}Al source [5,15,16,17,18,19,20]. These hot stars form the final phase of post-main-sequence massive stars [21]. W-R stars produce ^{26}Al but no ^{60}Fe, so they fit the requirements. Although stellar evolution models differ in the amount of ^{26}Al produced [22.23,24,25,26,27], an analysis of various stellar evolution models suggests that W-R stars with initial mass over about 50 $M_\odot$ can provide the requisite amount of ^{26}Al to seed the early solar system in most models. The ^{26}Al is mostly produced during the main-sequence stage, but is mainly emitted in the strong mass-loss that follows the main-sequence phase, including the W-R phase (Figure 1).

Massive stars have strong supersonic winds, with wind speeds of order 1000-2000 km s^{-1}, and mass loss rates of 10^{-7} to $10^{-4.5}$ $M_\odot$ yr^{-1}. These winds sweep up the surrounding medium to form large wind-blown bubbles, having a low density hot interior surrounded by a high-density cool shell [28,29]. The combined action of wind shocks and ionization fronts due to the hot stars can lead to local increases in the density of the shell, leading to collapse of the shell in some places and the formation of new stars [30,31]. This is known as triggered star formation, and is often seen in bubbles around massive stars [32,33,34,35], including W-R stars [36].

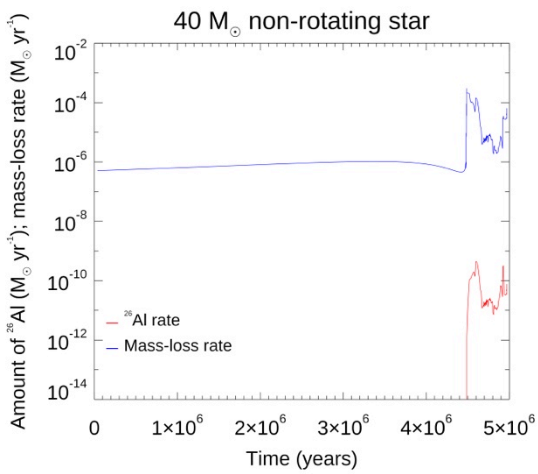

Figure 1: The evolution of the wind mass-loss rate (blue) in a non-rotating 40 M_ star (parameters from [22]). The mass-loss rate is steady throughout the main-sequence phase, but increases dramatically in the red supergiant and W-R phases. In red is the amount of ^{26}Al lost per year via the wind [37]

In our detailed model of the formation of the solar system [37, Figure 2], the collapse of one such shell around a W-R star leads to the formation of the dense cores that give rise to the sun and planetary disk. Aluminium-26 is produced during the evolution of the massive star and released in the wind during the W-R phase. The ^{26}Al subsequently condenses into dust grains that are seen around W-R stars in infrared observations [38,39], and estimated to be about 1μm in size [40]. These large dust grains can survive passage through the reverse shock and the low density shocked wind, reach the dense shell swept-up by the bubble, detach from the decelerated wind with the wind velocity and are then injected into the shell. The dust grains are destroyed in the shell due to ablation and non-thermal sputtering, although a small fraction may survive, while the ^{26}Al is released into the shell. The shell thickness and density varies, as does the velocity of the dust grains, so they will penetrate to different depths in different parts of the shell. Therefore, while some regions may be rich in ^{26}Al, others will not possess significant amounts of ^{26}Al. Such a diversity in ^{26}Al abundance is also seen in meteorites. FUN (with fractionation and unidentified nuclear isotope anomalies)

CAIs [41,42,43] and hibonite rich CAIs are generally ^{26}Al poor [44], whereas spinel hibonite spherules are consistent with the canonical ^{26}Al/^{27}Al ratio [45].

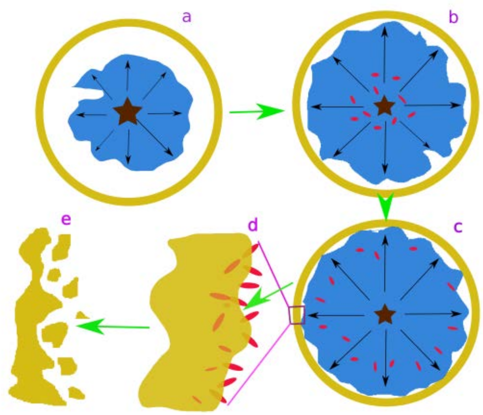

Figure 2: Cartoon version of our model of the formation of the solar system. (a) A massive star forms. Its strong winds and ionizing radiation build a wind-blown bubble. The blue region is wind-blown region; yellow is the dense shell. An ionized region (white) separates them. (b) The bubble grows with time as the star evolves into the W-R phase. At the same time, dust forms in the wind close in to the star, and we assume the ^{26}Al condenses into dust. (c) Dust is carried out by the wind towards the dense shell. (d) The wind is decelerated at the shell, dust detaches from the wind and continues onward, penetrating the dense shell. (e) Triggered star formation is underway. Some material in the shell collapses to form dense molecular cores which will give rise to solar systems. [37]

The final fate of the W-R star is model dependent. In some models the star collapses directly to a black hole [46], with no explosive nucleosynthesis accompanied by production of ^{60}Fe. In other models the star explodes as a SN, but the ejecta distribution is asymmetric [47,48] making it likely that no ejecta will reach the proto-solar system. Even if it does, it is unlikely that the hot, fast ejected material can easily mix with the cooler material in the solar system [49]. Thus it is unlikely that additional ^{60}Fe will be injected into the proto-solar system. The ^{60}Fe present comes from swept-up Galactic material, that could have been cooling for the several million-year stellar lifetime.

We estimate that 1-16% of all stars could have been formed via triggered star formation in bubbles.

References: [1] Lee T. et al (1976), *Geo. Res. Let., 3*, 109-112. [2] Jacobsen et al. (2008) *EPSL, 272*, 353-364. [3] McPherson et al. (1995) *Meteoritics, 30*, 365-386. [4] Tang H. and Dauphas N. (2012) *EPSL, 359*, 248. [5] Tang H. and Dauphas N. (2015) *ApJ, 802*, 22. [6] Huss et al. (2009) *Geo. Et Cosmo. Acta., 73*, 4922-4945. [7] Diehl R et al. (2006), *Nature, 439*, 45-47. [8] Meyer B. and Clayton D. (2000) *From Dust to Terrestrial Planets*, 133–152. Springer. [9] Wasserburg et al. (2006) *Nuc. Phys. A, 777*, 5-69. [10] Marhas K. et al. (2002) *Sci., 298*, 2182-2185. [11] Duprat J. and Tatischeff V. (2007) *ApJL, 671*, 69-72. [12] Cameron A., and Truran J. (1977) *Icarus, 30*, 447-461. [13] Kastner, J. H., and Myers, P. C. (1994), ApJ, 421, 605. [14] Wasserburg, G. J., Karakas, A. I., and Lugaro, M. (2017) ApJ, 836,126. [15] Arnould M. et al. (1997), *A&A, 321*, 452-464. [16] Arnould M. et al. (2006), *A&A, 453, 653-659*. [17] Gaidos E. et al. (2009) *ApJ, 696*, 1854. [18] Gounelle M. and Meynet G. (2012) *A&A, 545*, A4. [19] Young, E. D. (2014) E&PSL, 392, 16. [20] Young, E. D. (2016) ApJ, 826, 129. [21] Crowther, P. A. (2007) ARA&A, 45, 177. [22] Ekstrom, S. et al. (2012), *A&A*, 537, A146. .[23] Georgy, C., et al. (2012), *A&A*, 542, A29. [24] Georgy, C., et al. (2013), *A&A*, 558, A103. [25] Limongi, M. & Cieffi, A, (2006), *ApJ*, 647, 483. [26] Palacios, A. et al. (2004), *A&A*, 429, 613. [27] Langer, N. et al. (1995), *ApSS*, 224, 275. [28] Dwarkadas, V. V. and Rosenberg, D. (2013) HEDP, 9, 226. [29] Toala, J. A., & Arthur, S. J. (2011) ApJ, 737, 100. [30] Elmegreen, B., & Lada, C. (1977), *ApJ*, 214, 725. [31] Lefloch, B. & Lazareff, B. (1994), *A&A, 289, 559.* [32] Deharveng, L. et al. (2003), *A&A, 408, L25.* [33] Deharveng, L. et al. (2005), *A&A, 433, 565.* [34] Zavagno, A. et al. (2007), *A&A, 472, 835* [35] Brand, J. et al. (2011), *A&A, 527, 62.* [36] Liu, T. et al. (2012), *ApJ, 751, 68*. [37] Dwarkadas, V. V., Dauphas, N., Meyer, B., Boyajian, P., and Bojazi, M., (2017), ApJ, 851, 147 [38] Rajagopal, J, et al. (2007), *ApJ, 671, 2017.* [39] Marchenko, S. & Moffat, T. (2007), *ASPC, 367, 213.* [40] Marchenko, S. et al. (2002), *ApJ*, 565, L59. [41] Esat, T. M., Papanastassiou, D. A., and Wasserburg, G. J. (1979), in LPSC Conf Vol 10, 361-363. [42] Armstrong, J. T., Hutcheon, I. D., and Wasserburg, G. J. 1984, in LPSC Conference, Vol. 15, 15. [43] MacPherson, G. J., Bullock, E. S., Janney, P. E., et al. 2007, in LPSC Conf, Vol. 38, 1378. [44] Koop, L., Davis, A. M., Nakashima, D., et al. 2016, GeoCoA,189, 70. [45] Liu, M.-C., McKeegan, K. D., Goswami, J. N., et al. 2009, GeoCoA, 73, 5051. [46] Sukhbold, T., & Woosley, S. E. 2016, ApJL, 820, L38. [47] Maeda, K., Kawabata, K., et al. (2008), Science, 319, 1220. [48] Mazzali, P. A., Kawabata, K. S., Maeda, K., et al. (2005), Science, 308, 1284. [49] Goswami, J. N., and Vanhala, H. A. T. 2000, Protostars and Planets IV, 963