Triggered Star Formation inside the Shell of a Wolf-Rayet Bubble as the Origin of the Solar System

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Abstract. A constraint on Solar System formation is the high ^{26}Al/^{27}Al abundance ratio, 17 times higher than the average Galactic ratio, while the ^{60}Fe/^{56}Fe value was lower than the Galactic value. This challenges the assumption that a nearby supernova was responsible for the injection of these short-lived radionuclides into the early Solar System. We suggest that the Solar System was formed by triggered star formation at the edge of a Wolf-Rayet (W-R) bubble. We discuss the details of various processes within the model using numerical simulations, and analytic and semi-analytic calculations, and conclude that it is a viable model that can explain the initial abundances of ^{26}Al and ^{60}Fe. We estimate that 1%-16% of all Sun-like stars could have formed in such a setting.

Keywords. methods: analytical, methods: numerical, Solar System: formation, stars: mass loss, stars: winds, outflows, stars: Wolf-Rayet, ISM: bubbles

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 $\sim$17 times higher than the average Galactic ratio (Lee *et al.* 1976, Jacobsen *et al.* 2008, MacPherson *et al.* 1995, Tang & Dauphas 2012). 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 (Tang & Dauphas 2012, Tang & Dauphas 2015). The abundance of ^{26}Al as inferred in meteorites is too high (Tang & Dauphas 2012, Huss *et al.* 2009) to be accounted for by long-term Galactic chemical evolution (Tang & Dauphas 2012, Meyer & Clayton 2000, Wasserburg *et al.* 2006) or early Solar System particle irradiation (Marhas *et al.* 2002, Duprat & Tatischeff 2007).

These results challenge the assumption that a nearby supernova (SN) was responsible for the injection of these short-lived radionuclides into the early Solar System, as had been suggested almost 40 years ago by Cameron & Truran (1977), unless one can explain why a SN injected only ^{26}Al, but did not manage to inject any ^{60}Fe.

Besides SNe, sources of ^{26}Al include AGB stars and Wolf-Rayet (W-R) stars. The probability of an AGB star being found near the Sun is extremely small (Kastner & Myers 1994). Wasserburg *et al.* (2017) showed that an AGB star is unlikely to simultaneously explain the initial Solar System abundance of ^{26}Al, ^{60}Fe, ^{107}Pd and ^{182}Hf.

This leaves W-R stars as the source of ^{26}Al in the early Solar System (Tang & Dauphas 2015, Arnould *et al.* 1997, Arnould *et al.* 2006, Gaidos *et al.* 2009, Gounelle & Meynet
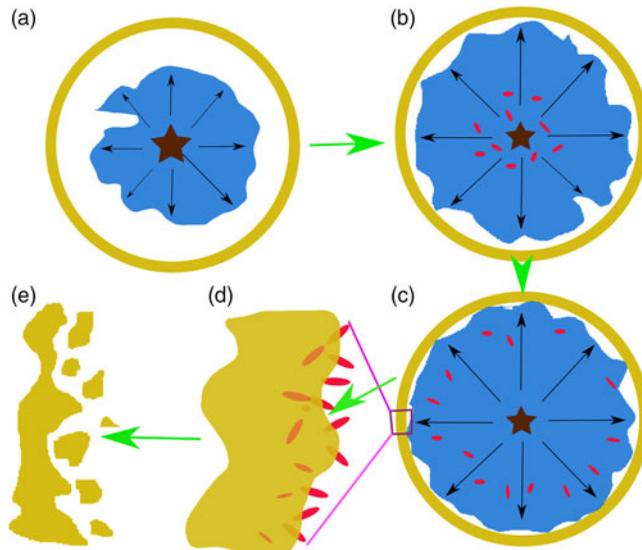
Figure 1. Cartoon version of our model of the formation of the Solar System. (a) Strong winds and ionizing radiation from a massive star build a windblown bubble. Blue region is the windblown region, yellow is the dense shell. (b) The bubble grows with time as the star evolves into the W-R phase. Dust forms in the wind close in to the star, and we assume that the ^{26}Al condenses into dust grains. (c) Dust is carried out by the wind toward the dense shell. (d) Wind is decelerated at the shell, dust detaches from the wind and penetrates the dense shell where it is destroyed, releasing the ^{26}Al. (e) Triggered star formation in the shell will give rise to various solar systems, including ours.

2012, Young 2014, Young 2016). These hot stars form the final phase of post-main-sequence massive stars above $\sim 25\,M_\odot$ (Crowther 2007). W-R stars produce ^{26}Al, which is carried out in their winds, but no ^{60}Fe. Although stellar evolution models differ in the amount of ^{26}Al produced, an analysis of various stellar evolution models (Langer *et al.* 1995, Palacios *et al.* 2005, Limongi & Cieffi 2006, Ekstrom *et al.* 2012, Georgy *et al.* 2012, Georgy *et al.* 2013) 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 itself is mainly produced during the main-sequence stage, but is mostly emitted in the strong mass-loss that follows the main-sequence phase, including the W-R phase.

Massive stars have strong supersonic winds, with wind speeds of order 1000-2000 km s^{-1}, and mass loss rates of 10^{-7} to $10^{-4.5}\,M_\odot yr^{-1}$ (Crowther 2007). 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 (Toala & Arthur 2011, Dwarkadas & Rosenberg 2013). 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 certain regions, and the formation of a new ensemble of stars (Elmegreen & Lada 1977, Lefloch & Lazareff 1994). This is known as triggered star formation, and is often seen in bubbles around massive stars (Deharveng *et al.* 2003, Deharveng *et al.* 2005, Zavagno *et al.* 2007, Brand *et al.* 2011). At least one case of triggered star formation around a W-R star is known (Liu *et al.* 2012).

In our detailed model of the formation of the Solar System (Dwarkadas *et al.* 2017, Figure 1), the collapse of a wind-blown shell around a W-R star leads to the formation of the dense cores that give rise to the Sun and planets. Aluminium-26 is produced during the H-burning lifetime of the massive star, and is found in the He core and in the H left behind by the receding core at the end of H-burning (Limongi & Cieffi 2006). In W-R stars these layers are ejected mainly through mass-loss, which reaches deep into

the interior. The ^{26}Al subsequently condenses into dust grains that have been observed around W-R stars in infrared observations (Tuthill *et al.* 1999, Rajagopal *et al.* 2007, Marchenko & Moffat 2007), and estimated to be about 1μm in size (Marchenko *et al.* 2002). Due to the large size of the grains and low density within the bubble, the dust grains survive passage through the reverse shock and shocked wind, reach the dense shell swept-up by the bubble, detach from the decelerated wind with the wind velocity, and are subsequently 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, as well as the velocity of the dust grains, vary over a considerable range, with the result that the grains 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 (Esat *et al.* 1979, Armstrong *et al.* 1984, Macpherson *et al.* 2007) and hibonite rich CAIs are generally ^{26}Al poor (Koop *et al.* 2016), whereas spinel hibonite spherules are consistent with the canonical ^{26}Al/^{27}Al ratio (Liu *et al.* 2009).

The final fate of the W-R star is model dependent. In some models most massive W-R stars collapse directly to a black hole (Sukhbold *et al.* 2016), 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 (Mazzali *et al.* 2005, Maeda *et al.* 2008) 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 (Goswami & Vanhala 2000), and therefore 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. Assuming that the IMF of the triggered stars is the same as that of the field stars, we estimate that 1-16% of all Sun-like stars could have been formed via triggered star formation in bubbles.

The model thus explains the abundance of ^{26}Al and ^{60}Fe in the early Solar System. Any such model must also be able to explain other short-lived radionuclides found in meteorites, such as ^{36}Cl, ^{41}Ca, ^{53}Mn etc. These investigations are in progress. Another caveat is that if all the dust grains are not destroyed within the shell, then some dust grains should remain that reflect the W-R composition. So far no dust grains in meteorites have been ascribed to W-R stars, and it is not even clear what a definitive sign of W-R origin would be. Finally, detailed models of ^{26}Al condensation onto dust grains under non-equilibrium conditions are needed to confirm that the ^{26}Al will condense onto dust grains.

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Discussion

You-Hua Chu: WR stars have three varieties – nitrogen sequence, carbon sequence and oxygen sequence. Dust in stellar winds is found around WC stars, bubbles are found mostly around WN stars. These need to be carefully distinguished, instead of lumped together as WR stars.

Dwarkadas: While dust is mostly seen around WC stars, it is not a problem for our model as long as dust is formed in some stage and present around the star so that ^{26}Al can condense onto it. Wind bubbles are certainly found in all stages, not just in the WN stage. They do not suddenly appear in one stage and disappear in the next. A quick search of the literature reveals several examples of nebulae around WR stars in the WC phase, e.g., Stock & Barlow 2010 MNRAS, 409, 1429; Drissen, Shara and Moffett, 1991, AJ, 101, 1659; Cappa *et al.* 2005, A&A, 436, 155; Marston, A. 1997, ApJ, 475, 188. Marston notes that nebulae around WC stars are larger and could be missed. So there is no problem with having dust in some phase as the bubbles do exist in all phases.