

Meteoritic Constraints on the Origins of our Solar System Vikram V. Dwarkadas¹, Peter H. Boyajian¹, Michael Bojazi², Bradley S. Meyer², and Nicolas Dauphas³, ¹Dept. of Astronomy and Astrophysics, University of Chicago, 5640 S Ellis Ave, ERC 569, Chicago, IL 60637 (vikram@oddjob.uchicago.edu), ²Dept. of Physics and Astronomy, Clemson University, Clemson, SC, ³Origins Lab, Department of the Geophysical Sciences and Enrico Fermi Institute, University of Chicago

Introduction: A critical constraint on solar system formation is the high abundance of ^{26}Al ($t_{1/2}=0.7$ Myr). The abundance of ^{26}Al as inferred in meteorites is ~ 17 times larger than the average ISM abundance at solar system birth from gamma-ray astronomy [1,2,3,6], which is too high [4,5,6] to be accounted for by long-term Galactic chemical evolution [7, 4, 8] or early solar system particle irradiation [9, 10].

This led to suggestions starting 40 years ago [11] that a nearby supernova (SN) explosion triggered the collapse of a molecular cloud and the formation of the solar system. ^{26}Al was created via stellar and SN nucleosynthesis, and injected into the protostellar cloud by the shock wave. This suggestion has been followed up by several authors [7,12, 13]. If correct, one would expect this to be accompanied by a high abundance of ^{60}Fe ($t_{1/2}=2.6$ Myr) which is produced in SN explosions. Recent work instead found that the $^{60}\text{Fe}/^{56}\text{Fe}$ ratio at solar system formation is about an order of magnitude lower than the average ISM value, inconsistent with direct injection from a nearby SN [6, 14].

Any potential model of solar system formation thus needs to explain both high $^{26}\text{Al}/^{27}\text{Al}$ and low $^{60}\text{Fe}/^{56}\text{Fe}$ ratios. The distribution of ^{26}Al in the Galaxy closely traces the distribution of very massive stars, making Wolf-Rayet (W-R) stars and core-collapse SNe the primary candidates for ^{26}Al production [20]. The former are stars with initial mass ≥ 25 , which have lost their H and possibly He envelopes. In a study of the Carina region using INTEGRAL data, [21] found that the ^{26}Al signal could not be accounted for by supernovae alone, and the fraction of ^{26}Al ejected in W-R stars is high, indicating strong wind ejection of ^{26}Al . ^{26}Al has also been seen towards other star forming regions such as Cygnus [22], Orion [23], and Scorpius-Centaurus [24]. Many authors have suggested that stellar winds from massive stars, could be the source of ^{26}Al in the early solar system. [5, 14, 15, 16, 19, 45].

Using a combination of semi-analytic calculations, astronomical observations, and numerical modeling, in this presentation we advance the idea that our solar system was born inside a Wolf-Rayet wind bubble. We show that this can simultaneously explain both the high ^{26}Al and low ^{60}Fe abundance.

Wolf-Rayet Bubbles: W-R stars are post-main-sequence, hot massive stars which have strong winds with terminal velocities of $1000\text{--}2000\text{ km s}^{-1}$ [31]. The combined action of the supersonic winds and ionizing radiation results in the formation of photo-ionized wind-blown bubbles around the stars, consisting of a low-density interior surrounded by a high-density shell (Fig. 1). Most of the volume is occupied by a low-density high-temperature plasma.

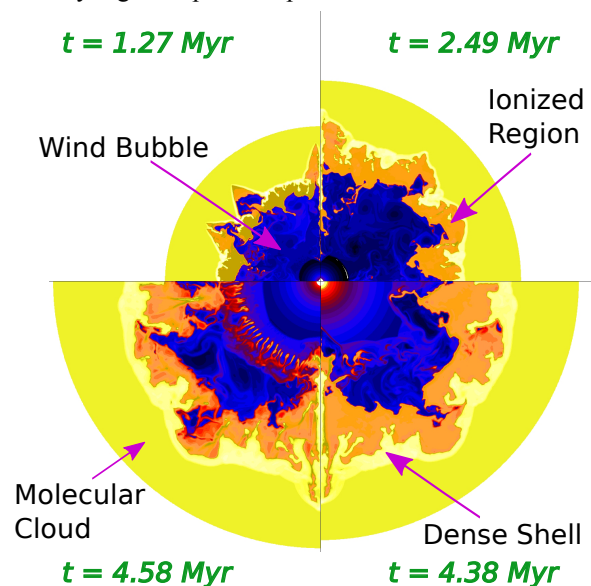


Figure 1: Density at 4 epochs in the evolution of a wind-blown bubble around a $40 M_{\odot}$ star, at (clockwise from top left) 1.27, 2.49, 4.38 and 4.58 Myr. Note that the shell is unstable to several instabilities, related to both the hydrodynamics and the ionization front, which cause fragmentation and the formation of dense filaments and clumps [39, current work].

^{26}Al Yields from massive stars: In Figure 2 we show the ^{26}Al yields from stars with initial mass $> 20 M_{\odot}$ [25,26,27,28,29,30]. Newer yields (1-4) take into account stellar rotation and improved mass-loss rates [25,26, 27]. The horizontal lines show the efficiency of mixing η , defined as the fraction of ^{26}Al required to mix with the dense shell of swept-up material to provide sufficient ^{26}Al to account for the early solar system budget of 3.3 parts per billion [19]. Stars above $50 M_{\odot}$ generally provide sufficient ^{26}Al . The wind ^{60}Fe yield is negligible.

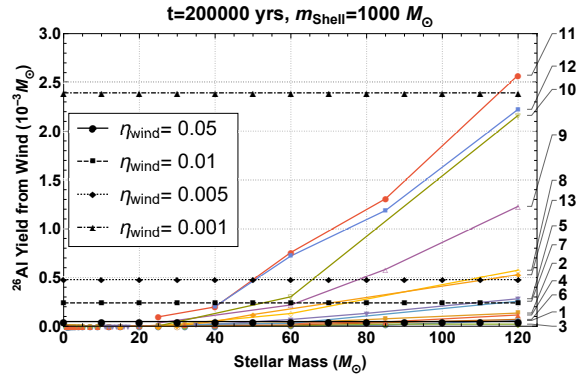


Figure 2

Wind Bubbles as Stellar Nurseries: Star formation at the boundaries of wind-bubbles around O and B stars has been revealed in astronomical observations [32,33,34,35]. Molecular cores undergoing gravitational collapse due to external pressure from the surrounding gas have been found around W-R star HD 211853 [36]. This stochastic star-formation is described in the context of two models, the 'collect and collapse model' [37] and the 'radiation-driven implosion' model [38].

Injection of ^{26}Al from the Wind to the Solar System: Injection of the ^{26}Al from the wind into the early solar nebula is an important ingredient. This topic has been studied mainly in the context of injection by a SN. [12,13] have shown that the injection efficiency due to hydrodynamic mixing between the SN shock wave and the collapsing cores is small, of order a few percent. This occurs late in the SN evolution, when it has reached the radiative stage and slowed down $< 100 \text{ km s}^{-1}$ (although see [40]). The W-R wind velocity substantially exceeds this value, while the density is much lower than in the SN ejecta. The efficiency of mixing will therefore be reduced. Winds sweeping past high-density cores will lead to shearing and the growth of Kelvin-Helmholtz instabilities at the interface, stripping material away. Hydrodynamic mixing does not appear a viable mechanism.

We suggest that ^{26}Al condenses onto, and is injected mainly via dust grains (see also [17,41]). Dust is seen around WC stars [42,43], although the formation mechanism at high temperatures is not well understood. Analysis of IR emission shows that dust forms close in to the star, with the grains estimated to be $\sim 1 \mu\text{m}$ in size [44]. The stopping distance of $1 \mu\text{m}$ size grains in bubbles is several parsecs, exceeding the size of the bubble in the high density molecular cloud. The grains can survive passage through the reverse shock and the low density shocked wind, and reach the outer dense shell. The grains would then be injected into the

high density cores, penetrating depths of 1 to several hundred AU depending on the density.

Finally, the massive star will explode as a SN of Type Ib/c. We have explored why the material ejected in the explosion, which contains both ^{26}Al and ^{60}Fe , may not be able to contaminate the early solar system.

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