Was our Solar System Born inside a Wolf-Rayet Bubble? Vikram V. Dwarkadas[1], Peter H. Boyajian[1], Michael Bojazi[2], Alex Heger[3], Bradley. S. Meyer[2], and Nicolas Dauphas[4], [1]Dept. of Astronomy and Astrophysics, University of Chicago, 5640 S Ellis Ave, ERC 569, Chicago, IL 60637 (vikram@oddjob.uchicago.edu), [2]Dept. of Physics and Astronomy, Clemson University, Clemson, SC, [3]Monash University, Wellington Road, Victoria, Australia, [4]Origins 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), ~17 times larger than the average ISM abundance at solar system birth from gamma-ray astronomy [1,2,3,6]. The abundance of ^{26}Al as inferred in meteorites 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].

Almost 40 years ago, [11] suggested that a nearby supernova (SN) explosion triggered the collapse of a molecular cloud and the formation of the solar system. ^{26}Al created via stellar and SN nucleosynthesis, was 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). Recent work instead found that the ^{60}Fe/^{56}Fe ratio at solar system formation is about an order of magnitude lower that 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}Al/^{27}Al and low ^{60}Fe/^{56}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 $M_\odot$, 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].

*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**.*

^{26}Al Yields from massive stars: In Figure 1 we have plotted 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 new metallicities, stellar rotation and improved mass-loss rates [25,26, 27]. It is clear that a single massive star provides at

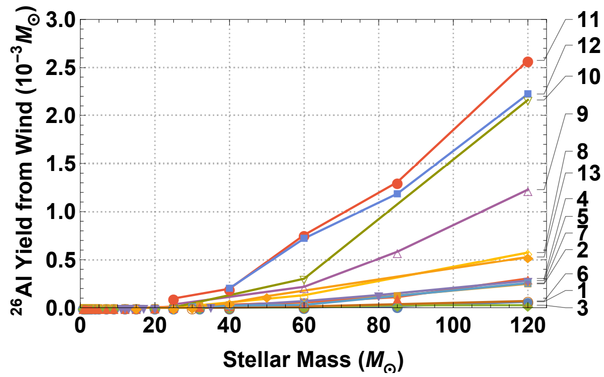

Figure 1

least 10^{-4} $M_\odot$ of ^{26}Al, sufficient (even after some dilution) for the entire early solar system budget [16], where the initial concentration was 3.3 parts per billion [19]. The more massive the star the higher the ^{26}Al yield. The ^{60}Fe yield from the wind itself is negligible - ^{60}Fe in the proto-solar nebula arises from the swept-up material, expelled by a previous generation of stars.

Wolf-Rayet Bubbles: W-R stars form the post-main-sequence phase of massive O and B-type main sequence stars. These stars have winds with terminal velocities of 1000-2000 km s^{-1} [31]. The high surface temperature of these hot stars results in a large number of ionizing photons. 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. 2). Most of the volume is occupied by a low-density high-temperature plasma.

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 triggered or stochastic star-formation is well understood in the context of two models, the `collect and collapse model' [37] and the `radiation-driven implosion' model [38].

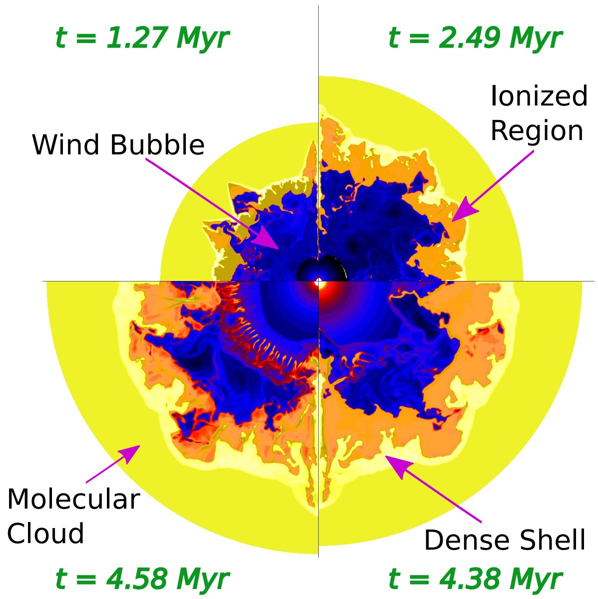

Figure 2: Density at 4 epochs in the evolution of a wind-blown bubble around a 40 $M_{\odot}$ star, at (clockwise from top left) 1.27, 2.49, 4.38 and 4.58 Myr. Note that the shell is unstable to several instabilities, related to both the hydrodynamics and the ionization front, which cause fragmentation and the formation of dense filaments and clumps [39, current work].

Injection of ^{26}Al from the Wind to the Solar System: The important ingredient remaining is the injection of the ^{26}Al from the wind into the early solar system. 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 km s^{-1} (although see [40]). The W-R wind velocity substantially exceeds this value, and they have a much lower density than 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 instead that ^{26}Al condenses onto, and is injected mainly via dust grains (see also [17,41]). Dust is seen around WN and 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 large in size, ~ 1μm [44]. The stopping distance of μm 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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