Investigating a Stellar Wind Origin for High ^{26}Al and Low ^{60}Fe in the Early Solar System. V. V. Dwarkadas[1], N. Dauphas[2], and B. S. Meyer[3], [1]Department 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 (dauphas@uchicago.edu), [3]Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978 USA (mbradle@clemson.edu),

Introduction: Understanding the formation of the solar system requires an astrophysical understanding of how, where and in what quantities extinct radionuclides are produced and transported. To study this, we have started a multi-scale investigation coupling stellar nucleosynthesis, high-resolution simulation of stellar wind-interstellar medium (ISM) interactions, and coarser scale simulation of mixing in molecular clouds, to track the fate of newly synthesized radionuclides.

A critical constraint on solar system formation is the high abundance of ^{26}Al ($t_{1/2}$=0.7 Myr), which exceeds by a factor of ~17 the average ISM abundance at solar system birth from gamma-ray astronomy [1,2,3]. ^{26}Al in meteorites is in too high abundance [4,5,6] to be accounted for by long-term chemical evolution of the Galaxy [7, 4, 8] or early solar system particle irradiation [9, 10]. Instead, ^{26}Al must have come from the direct injection from a nearby supernova [7,11,12], stellar winds from massive stars [5, 13, 14, 15, 16], or winds from an AGB-star [8]. The latter is unlikely, because of the remote probability of finding an evolved star at the time and place of solar system formation [6,17].

It has been suggested that 26Al in meteorites may have come from the injection of a nearby supernova that triggered the solar molecular cloud core into collapse [11, 18]. If correct, one would expect to also find high abundance of ^{60}Fe ($t_{1/2}$=2.6 Myr). Recent work found a ^{60}Fe/^{56}Fe ratio at solar system formation that is a factor of ~30 lower that the average ISM value, which is inconsistent with direct injection from a nearby supernova [6, 19]. We are thus confronted with the challenge of explaining both high ^{26}Al/^{27}Al and low ^{60}Fe/^{56}Fe ratios. An appealing possibility is that ^{60}Fe was derived from the Galactic background, while ^{26}Al was derived from winds of one or several massive stars [6]. Indeed in massive stars, ^{26}Al is produced in more external regions than ^{60}Fe.

We are carrying out theoretical modeling coupled with multi-scale high-resolution multi-dimensional ionization-gasdynamics simulations to test this scenario. Our team has adopted a multi-pronged approach to tackle this problem. One avenue is to investigate the evolution of the winds from massive stars, especially Wolf-Rayet stars (which are responsible for up to 50% of the production of ^{26}Al in the ISM [20]), and the mixing of stellar winds with the surrounding medium. This is followed by detailed computations of the supernova ejecta expanding within this medium. The flux estimates resulting from these calculations are used in a 3D model of chemical evolution, in which nucleosynthesis, transport and radioactive decay of nuclides are tracked. This will allow us to investigate whether Sun-like stars can form from wind-contaminated material enriched in ^{26}Al and normal ^{60}Fe.

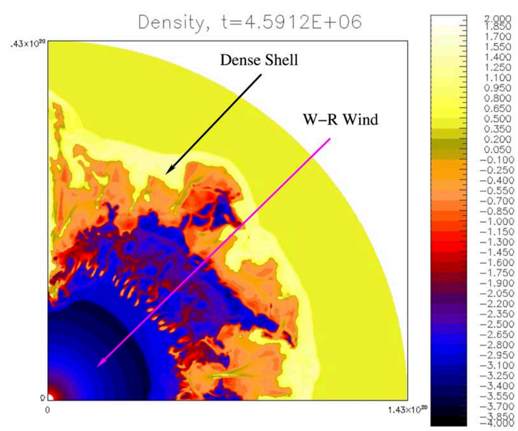

Figure 1: Density snapshot from the evolution of a wind-blown bubble around a 40 solar mass star at ~4.6 Myr, using our ionization-gasdynamics code *Avatar*. The star spends most of its life as a main-sequence star. The size of the bubble is set in this phase. The interior is low density surrounded by a high-density shell. It leaves the main sequence to become a Red Supergiant star, followed by the Wolf-Rayet phase. The filamentary structure seen is a direct result of instabilities due to the mixing of layers of different densities. The Wolf-Rayet wind (innermost) has a very high momentum and mixes all the material ejected in the previous phases within the bubble, thus altering the composition of the material. Wind material from all phases is confined within the dense shell of the bubble, and not mixed with the ISM. The subsequent supernova shock wave can destroy the dense shell and mix the stellar ejecta with the surrounding ISM. An outstanding question is whether SN-driven bubble-ISM mixing can occur without delivering too much ^{60}Fe.

Formation of Wind-Blown Bubbles containing ^{26}Al around Massive Stars: A critical component of this investigation, and one that has not received much attention in the past, is the production and mixing of ^{26}Al from massive (> 8 solar masses) stars, especially Wolf-Rayet (W-R) stars. The main difficulty is that winds from massive stars form wind-blown bubbles around the stars, consisting of a low-density interior surrounded by a high-density shell, and do not mix directly with the surrounding medium. Therefore, *the ^{26}Al that is being produced cannot be immediately mixed with the ISM, but is contained within the dense bubble (Figure 1).* Another mechanism is required to break up the dense shell and mix the contents of the bubble with the ISM, leading to a delay in the mixing. Instabilities within the bubble shell may lead to some leakage, but simulations and observations suggest this is not a large effect (Figure 1). The ^{26}Al and other products that are transported via mass-loss can only be mixed in with the ISM upon the impact of the subsequent shock wave that arises when the massive star collapses as a supernova (SN). The shock wave expands within the bubble until it collides with the dense shell, breaking it apart in most cases. In some scenarios, particularly when the shell has swept-up a large amount of interstellar material, the shock could become radiative and get trapped within the dense shell [21]; in these cases the ^{26}Al may never be released into the surrounding until the shock manages to emerge or the bubble dissipates over a much larger timescale.

In order to investigate these possibilities, we are carrying out a series of simulations investigating the various steps: (1) The formation of wind-blown bubbles around massive W-R stars of different initial masses, taking the evolution of the star and the stellar yields into account [22,23]. Abundance yields for massive stars were kindly provided by G. Meynet [24]. (2) The impact of the subsequent SN shock wave with the W-R shell and the release of the trapped wind-blown material, including ^{26}Al, as well as ^{26}Al synthesized in the SN explosion, into the surrounding medium. The SN ejecta also contribute the ^{60}Fe that will be found in the early solar system. (3) The subsequent mixing of the hot material with the cold surrounding medium to form the early solar system.

Analytic Solution for the Properties of Wind-Blown Bubbles: There exists a large parameter space of initial masses of stars, interstellar medium densities, SN shock parameters, mixing parameters and evolutionary variables, and it would be computationally prohibitive to simulate all of these with multi-dimensional simulations. We have therefore worked on a semi-analytic solution to describe the evolution of the wind bubbles. We have succeeded in deriving a solution that parameterizes the radius of the wind bubble in terms of the evolutionary parameters of the star, i.e. the star's mass, radius, temperature, luminosity, and Eddington parameter (which can be close to 1 for the very massive stars that may produce large amounts of ^{26}Al). This solution can be used in an evolutionary model to describe the radii of the bubbles evolving in a medium of given density, and can also provide the pressure and density within the bubbles [25]. It can be used to give the size of the bubbles due to a distribution of stars of various masses, and, combined with the yields from stellar evolution models, the composition of the material within each bubble, especially the amount of ^{26}Al contained within the bubble. Furthermore, it can provide some parameters needed to investigate the evolution of the subsequent SN shock wave within the bubble. We are currently working on describing the latter in a semi-analytic manner.

This is a multi-year project, and we are currently developing the necessary infrastructure, including various tools and concepts, to tackle the question of the ^{26}Al/^{60}Fe ratio in the early solar system. One component is the contribution of massive star winds, and therefore W-R bubble formation and disruption. *At this conference we will show representative simulations that illustrate various facets of the bubble evolution and SN shock impact relevant to this problem. We will then outline the analytic solution that we have derived for the bubble properties, its derivation including the inherent assumptions, and illustrate its use.*

Multi-Zone Mixing Calculations: The analytic solutions mentioned above will be included in a multi-zone calculation of the chemical evolution of the ^{26}Al/^{60}Fe ratio in the ISM due to a large ensemble of stars in the interstellar medium [26] .

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