PRODUCTION OF MANGANESE-53 IN A SELF-ENRICHING MOLECULAR CLOUD. M. J. Bojazi and B. S. Meyer, Department of Physics and Astronomy, Clemson University, Clemson, SC, 29634-0978, USA.

Introduction: The presence of short-lived radioactivities in the early Solar nebula has been inferred from excesses of their daughter isotopes embedded within primitive meteorites found and analyzed via various physical and chemical means over the last 50 years. The challenge is to reconcile the abundances of these short-lived radioactivities, as inferred from meteorites, to those as predicted from ongoing, continuous Galactic nucleosynthesis and then to use that information to infer the circumstances of the Solar System's birth. The abundances of several of the short-lived species are too large compared to expectations from continuous Galactic nucleosynthesis (e.g., [1]). One thus appeals to a recent injection of fresh stellar matter into the proto-solar cloud or enhanced stellar activity around the time of the Sun’s birth to account for the abundance of several short-lived species, such as $^{26}$Al and $^{41}$Ca.

The abundance of radioactive $^{53}$Mn (average lifetime of approximately 5.4 million years) presents a particular challenge to models that incorporate fresh stellar matter. Injection of a fraction of bulk supernova matter to account for the abundance of radioactivities, such as $^{26}$Al or $^{41}$Ca, yields orders of magnitude too much $^{53}$Mn (e.g., [2]). This overabundance of $^{53}$Mn is typically accounted for by considering a mass cut that divides ejecta that escapes the star from that which either falls into a black hole or otherwise is not injected into the proto-solar cloud (e.g., [2]). Models of production of short-lived species in molecular clouds also show overproduction of $^{53}$Mn. In this brief paper, we consider the role of a mass cut on the production of $^{53}$Mn in a model of star formation in a molecular cloud.

Massive Star Production of $^{53}$Mn: Manganese-53 is abundantly produced deep in the interior of stars via hydrostatic and explosive oxygen and silicon burning. Fig. 1 shows the mass fraction of $^{53}$Mn in the ejecta (as a function of interior mass coordinate) from an initially 40 Solar mass star [3]. The abundance of $^{53}$Mn is strongly concentrated towards the innermost zones in the stellar ejecta. Fig. 1 also shows that, if matter inside a mass cut at an interior mass of 3 Solar masses does not get ejected from the star, the ejecta yield of $^{53}$Mn will be significantly reduced. Stars with mass 25 times that of the Sun, or greater, are thought to have significant fallback onto a black hole [4]; thus, a mass cut of the type we envision here is certainly plausible.

Inhomogeneous Chemical Evolution Model: To consider the abundance of $^{53}$Mn in a self-enriching molecular cloud, we use the ICE (Inhomogeneous Chemical Evolution) code we have developed on top of the multi-zone component of NucNet Tools [5]. The multi-zone code includes a nuclear reaction network and an arbitrary number of zones distinguished by three labels. A zone is a collection of abundances of species in the reaction network and an arbitrary number
of user-defined mutable properties. At each time step, the multi-zone code sets up links between zones. Once the links between the zones are constructed, the code builds the network matrix and then simultaneously solves the abundance changes due to nuclear reactions and mixing.

To build the version of ICE for these calculations, we constructed an 8x8x8 cubic molecular cloud containing a total of 512 zones. Zones are sub cubes within the larger cube, and these sub cubes are labelled by indices (x,y,z) which give the three cartesian spatial coordinates. At each time step, ICE computes the number of stars formed in the cloud during the time step from a Poisson random distribution generator using an average star formation timescale of 1000 years. For each star that forms, we use a random number to determine the stellar mass from an initial mass function [6] and three random numbers to choose the sub cube in which to place the star. We record the star and its starting composition (the composition of the cloud from which it forms at the formation time). We also compute, from the stellar mass, the time the star will die (its lifetime). We keep track of the stars in a priority queue such that the star at the top of the queue is the first to die and eject its matter. When a star explodes, we mix the ejecta from that star into its local sub cube and pop the exploding star from the priority queue.

Results and Discussion: Fig. 3 shows the $^{53}\text{Mn}/^{55}\text{Mn}$ and $^{60}\text{Fe}/^{56}\text{Fe}$ abundance ratios for Sun-like stars with initial masses between 0.8 and 1.2 Solar masses in our calculation. For the stellar yields that did not include a mass cut, the $^{53}\text{Mn}/^{55}\text{Mn}$ ratio grows with the $^{60}\text{Fe}/^{56}\text{Fe}$ ratio. These ratios fall in a fairly tight array. The dashed lines show the approximate inferred initial abundances for $^{60}\text{Fe}$ and $^{55}\text{Mn}$. We choose two possible ratios for the initial $^{60}\text{Fe}$ abundance. A value of $2\times10^{-8}$ is that inferred from chondrules [8] while a value of $3\times10^{-7}$ is closer to that inferred from SIMs measurements [9,10]. If the $^{60}\text{Fe}/^{56}\text{Fe}$ ratio is $3\times10^{-7}$, then the $^{53}\text{Mn}/^{55}\text{Mn}$ ratio in stars formed in the molecular cloud will be $10\times$ too large compared to the Solar ratio. If the $^{60}\text{Fe}/^{56}\text{Fe}$ ratio is $2\times10^{-8}$, then we have little trouble accommodating the Solar $^{53}\text{Mn}/^{55}\text{Mn}$ ratio, particularly since we expect production of $^{53}\text{Mn}$ from type Ia supernovae as well as from massive stars.

If we include the mass cut in our stellar yields, the spread in the $^{53}\text{Mn}/^{55}\text{Mn}$ ratio is considerably larger for the $^{60}\text{Fe}/^{56}\text{Fe}$ ratio near $3\times10^{-7}$. In particular, there are stellar systems that form with the $^{60}\text{Fe}/^{56}\text{Fe}$ ratio near $3\times10^{-7}$ and with the $^{53}\text{Mn}/^{55}\text{Mn}$ ratio near the inferred Solar value. This larger spread arises from the fact that for the highest mass stars, production of $^{53}\text{Fe}$ is decoupled from that of $^{60}\text{Fe}$. While stars less than 25 Solar masses inject both $^{60}\text{Fe}$ and $^{53}\text{Mn}$, the very high mass stars eject $^{60}\text{Fe}$ without much $^{53}\text{Mn}$. This allows for the large spread in the $^{53}\text{Mn}/^{55}\text{Mn}$ ratio for a given $^{60}\text{Fe}/^{56}\text{Fe}$ ratio.

In conclusion, allowing for a mass cut in the highest mass stars, as suggested by some stellar evolution calculations [4], gives enough of a spread in initial stellar abundances to accommodate both $^{53}\text{Mn}$ and $^{60}\text{Fe}$, even for an initial $^{60}\text{Fe}/^{56}\text{Fe}$ ratio near $3\times10^{-7}$. Although not presented here, this molecular cloud model also shows $^{129}$I and $^{182}\text{Hf}$ abundances near the inferred Solar abundances for the $^{60}\text{Fe}/^{56}\text{Fe}$ ratio near $3\times10^{-7}$. The relevance of these results awaits a firmly established initial $^{60}\text{Fe}$ Solar abundance.

References: