NEUTRON STAR MERGERS AND THE SHORT-LIVED R-PROCESS RADIOACTIVITIES. M. J. Bojazi[1] and B. S. Meyer[1], [1]Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978, USA (mbojazi@clemson.edu)

Introduction: The discovery that ^{129}I had been alive in the early Solar System provided important clues about Galactic nucleosynthesis and the age of the elements [1]. The abundance in the early Solar System is now firmly established as $^{129}I/^{127}I = 10^{-4}$ (e.g., [2]), a number difficult to reconcile with steady Galactic nucleosynthesis (e.g., [3]), which calls for a number larger typically by a factor of ~10-100. Iodine-129 is made in the r-process of nucleosynthesis, and an explanation for its low abundance is that there was an interval of ~10^8 years between the last r-process event and Solar System formation [1].

Another short-lived r-process radioactivity is ^{182}Hf with an early Solar System abundance of $^{182}Hf/^{180}Hf = 10^{-4}$ [4]. Surprisingly, this abundance ratio is roughly in line with expectations from steady-state Galactic nucleosynthesis, and a long decay interval of ~10^8 years between the last r process and Solar System formation would leave the ^{182}Hf abundance too low.

Possible explanations to reconcile the abundances of ^{129}I and ^{182}Hf in the early Solar System include varying r-process yields [5] and contributions to ^{182}Hf from nucleosynthesis sources other than the r process, such as massive star shell nucleosynthesis (e.g., [3]) or the s process [6]. For the latter explanation, it is still necessary to understand why the ^{129}I is low and whether the extra source of ^{182}Hf can account for that isotope's abundance.

Neutron Star Mergers: While supernova explosions of massive stars have long been considered a plausible site for r-process nucleosynthesis, there were speculations that mergers of neutron stars could eject neutron-rich matter that would then undergo an r process [7,8]. These speculations appear to have been borne out with the recent stunning optical and infra-red observations of the electromagnetic counterpart to the gravitational wave event GW170817 [9]. Unlike supernovae, neutron star mergers are rare events that produce large amounts of r-process nuclides. In this brief paper, we use this idea to try to reconcile the abundances of ^{129}I and ^{182}Hf in the early Solar System.

Methods: To follow Galactic chemical evolution, we use the ICE (Inhomogeneous Chemical Evolution) code we have developed over the last several years [10]. We set up an annular region at the Solar radius in the Galaxy and broke it into 32 zones that communicated with nearest neighbors on a timescale of 3 x 10^6 years. We allowed stars to form in the zones with initial masses determined from the Kroupa initial mass function [11]. After stars died, we allowed them to eject matter into a "hot" zone which cools and mixes with the denser star-forming mass on a timescale of 2 x 10^7 years. We evolved the Galaxy for 5 x 10^8 years near the time of the Sun's birth and recorded the abundance of isotopes in Solar mass stars that formed during that time. The timescales for mixing between gas phases were chosen to get the resulting $^{60}Fe/^{56}Fe$ abundance ratio near ~3 x 10^{-8} in 1 Solar mass stars, agreement with abundance ratio inferred from chondrules [12].

We allowed binary star systems to form. Some of these systems evolve to form binary neutron star systems which we then allow to merge on a timescale of ~10^8 years and possibly eject r-process matter, including ^{129}I and ^{182}Hf.

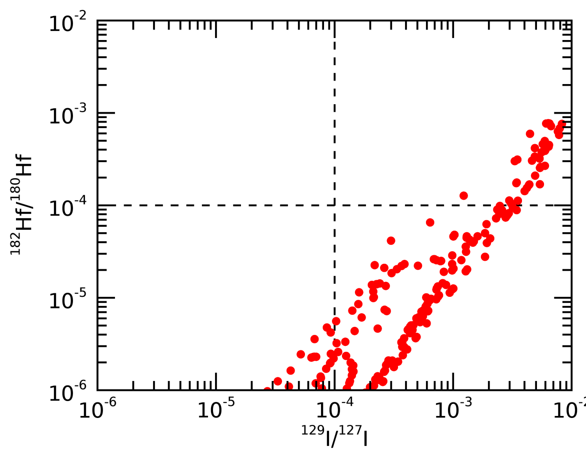

Figure 1: The $^{182}Hf/^{180}Hf$ and $^{129}I/^{127}I$ ratios in 1 Solar mass stars in the ICE calculation when only neutron-star mergers produce these isotopes. The abundances in the early Solar system are shown as dashed lines.

Results: Figure 1 shows the abundance ratios in 1 Solar mass stars that result from our calculation when only neutron star mergers produce ^{129}I and ^{182}Hf. In these calculations, we assumed all r-process events ejected 0.1 solar masses of r-process matter and that the abundance distribution of those ejecta were the same as the bulk Solar System abundances. This is a plausible assumption since low-metallicity halo stars, which incorporated ejecta of one or a few r-process events show an r-process abundance pattern in good agreement with the Solar System's pattern (e.g., [13]). As is evident, there is a large range in the abundance ratios. This is because each merger dumps a large amount of ^{129}I and ^{182}Hf into the local environment. Stars that form shortly after such an event and in its vicinity will have an abundance of those isotopes near the upper right end of the array of points in Fig. 1. As the short-lived radioactivities both decay, their abundance in the star-forming gas falls down along the array until another event injects new ^{129}I and ^{182}Hf. The time interval between mergers governs how great the spread is along the array. Importantly, the array does not pass through the intersection of the dashed lines, so there is no Solar mass star with abundance ratios comparable to those in the early Solar System.

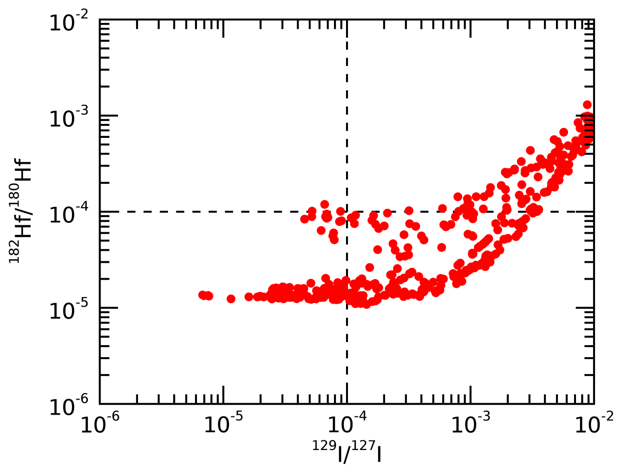

Figure 2: Same as Fig. 1 except that this model includes yields of ^{129}I and ^{182}Hf from shells of massive stars.

In Fig. 2 we show the results for a calculation that includes production of ^{129}I and ^{182}Hf from both neutron star mergers and from shell nucleosynthesis in massive stars. Although most Sun-like stars that form in this model do not have ^{129}I and ^{182}Hf abundances like that in the early Solar System, there are several that do. This model can thus plausibly account for the early Solar System's abundance of these species.

In Fig. 3, we show the results for a calculation that includes only production of ^{129}I and ^{182}Hf from the shells of massive stars. It is clear that this production site underproduces both isotopes; however, we see that this component provides an "end member" in the gas that, when mixed with the ejecta from neutron star mergers, can give ^{129}I and ^{182}Hf in agreement with their abundances in the early Solar System.

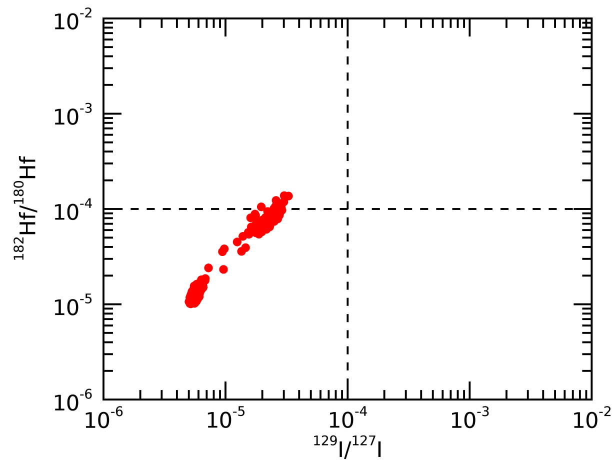

Figure 3: Same as Fig. 1 except that ^{129}I and ^{182}Hf only come from nucleosynthesis in the shells of massive stars.

Conclusion: The observation of r-process elements in the electromagnetic counterpart to GW170817 strongly suggests that neutron star mergers are the dominant source of r-process isotopes. Mergers by themselves cannot account for the early Solar System abundances of ^{129}I and ^{182}Hf because the r process always overproduces ^{129}I relative to ^{182}Hf. Nevertheless, the natural long time interval between rare neutron star mergers can allow the ^{129}I abundance to fall in star-forming gas, which, in combination with productions of ^{182}Hf in massive star shell nucleosynthesis, can plausibly result in abundances of these short-lived radioactivities that match those in primitive meteorittes.

References: [1] Reynolds J. (1960) *Phys. Rev. Lett., 4,* 8-10. [2] Brazzle R. H. et al. (1999) *GCA, 63,* 739-760. [3] Huss G. R. et al. (2009) *GCA, 73,* 4922-4945. [4] Kleine T. et al. (2005) *GCA, 69,* 5805-5818. [5] Wasserburg G. J. et a. (1996) *ApJ, 466,* L109-L113. [6] Lugaro M. et al. (2014) *Science, 345,* 650-653. [7] Lattimer J. et al. (1977) *ApJ, 213,* 225-233. [8] Meyer B. S. (1989) *ApJ, 343,* 254-276. [9] Kasen D. et al. (2017) *Nature, 551,* 80-84. [10] Bojazi M. and Meyer B. (2016) *LPS XLVII,* Abstract 3060. [11] Kroupa P. (2002) *Science, 295,* 82-91. [12] Tang H. and Dauphas N. (2015) *ApJ, 802,* 22. [13] Cowan J. et al. (1995) *ApJ, 439,* L51-54.