# HETEROGENEOUS R-PROCESS CHROMIUM AND TITANIUM EJECTA FROM CORE COLLAPSE SUPERNOVA EJECTA POLLUTED OUR SOLAR SYSTEM.

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**Introduction:** Our Sun was likely born as a protostar in a dense star forming region, in the vicinity of several massive (>8 $M_\odot$) stars. Very early in its history, the protoplanetary disk around the proto-Sun was impacted by debris from the supernova (SN) explosions of some of these massive stars. This caused an enrichment of the disk with short-lived radionuclides, the daughter products of which we observe in meteorites today. Injection of r-process nuclides resulting from SN events led to observed excesses of $^{54}$Cr, $^{50}$Ti, and r-process Mo in calcium-aluminum-rich inclusions (CAIs) [1–3]. In one scenario that can explain these r-process enrichments, these earliest solids derived their compositions from infalling material from a heterogenous molecular cloud, followed by inward transport to the inner disk, where CAIs condensed [4]. In addition, it is often surmised that the onset of our solar system was triggered by such an event [e.g., 5].

In this study, we investigate whether SN ejecta are intrinsically heterogeneous in r-process nuclides (Cr and Ti), and whether it is possible to inject r-process nuclides *alone* into a young protoplanetary disk. We also explore the chemistry and timeline by which r-process nuclides mix and pollute the protoplanetary disk, and compare it to the accreted s-process nuclides. Finally, we compare the known Cr and Ti isotopic compositions of stardust in meteorites to the ejecta compositions in core collapse supernova (CCSN).

**Methods:** The CCSN nucleosynthetic yields were determined by a 3D, spherically symmetric, CCSN simulation introduced in [6,7]. This model, called 15S, is based on a 15 $M_\odot$ progenitor star which is evolved using the 1D stellar evolution code TYCHO [8]. After core collapse and shock revival, the star is mapped into the 3D smoothed-particle hydrodynamics (SPH) code SNSPH [9,10] for 43 simulated hours until it is post-processed and isotope yields are captured using the Burnf code [11]. To avoid isotope abundances being influenced by rounding errors, only isotope mass fractions higher than $10^{-12}$ (relative to the mass of each of the roughly 1 million SPH particles) are included.

Maps of the SN ejecta were created using the SPH visualization software SPLASH [12] and plots were created in MATLAB. To ensure that the interior of the explosion can be investigated, cross-sections were formed which have a width of approximately 4.5 au in the Y direction. Additionally, SPH particles in the hydrogen envelope contain neither $^{50}$Ti nor $^{50,54}$Cr, we consider only the inner 6 au of the supernova ejecta.

**Results and Discussion:** *Stardust enriched in r-process nuclides.* Oxide stardust <100 nm in size shows large excesses in $^{54}$Cr and $^{50}$Ti [13–15]. The reported $\delta^{54}$Cr values of SiC stardust in acid leachates, on the other hand, tend to be indistinguishable from the terrestrial values within the experimental uncertainties [16], although $^{50}$Ti excesses have been observed [17,18]. Marhas et al. [19] reported 300-600 ‰ $^{54}$Cr excess in one unique SiC X grain. Graphite stardust exhibits large enrichments of $^{50}$Ti [20], although Cr isotopes have not been explored.

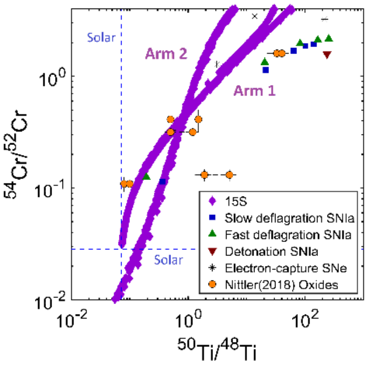

*Figure 1. Comparison of observed Cr and Ti isotope ratios in oxide stardust with isotopic compositions predicted by 3D CCSN model 15S. The excellent correlation makes CCSN potential sources of such stardust grains.*

Nittler et al. [15] favor an origin in SN Ia or electron capture supernovae (SNe) over Type II CCSN for the most extreme oxide grains because the O/C and O/Ne zones in 1D SN models that reach very high $^{54}$Cr/$^{52}$Cr ratios are also generally anomalous in $^{53}$Cr. This interpretation is in stark contrast to the solar $^{53}$Cr/$^{52}$Cr ratios observed in the grains. However, 1D models are not always suitable to constrain the origin of dust grains [7]. Comparison of the Cr and Ti compositions of the oxide stardust with the recent 3D CCSN models reveal an excellent match to the grain data (Fig. 1). The ejecta corresponding to 'Arm 1' (labeled in Fig. 1) is a better fit to the grain data and is associated with neutron-rich nuclides present in the outer parts of the explosion (>3 au). It was produced earlier than material in 'Arm 2' (<3 au) and would be injected first into a nearby protoplanetary disk.

*Injection of $^{54}$Cr and $^{50}$Ti into our protoplanetary disk.* A CCSN is the explosion of a massive star following the collapse of the iron core. The subsequent formation of a neutron star results in an enormous neutrino flux and a neutron-rich environment in the outflowing ejecta, where stardust grains form with very low $^{12}$C/$^{13}$C and $^{14}$N/$^{15}$N isotope ratios [7]. The material ejected after such an explosion is distributed, often asymmetrically, via the growth of Rayleigh-Taylor (R-

T) instabilities. These instabilities occur where a shell of dense, shocked ejecta is slowly accelerated by lower-density shocked circumstellar material and results in R-T fingers of dense ejected gas protruding into the surrounding medium.

We investigated the chemistry and dynamics of the ejecta in the 15S CCSN model. The abundance of carbon is highest in its outer regions, extending from halfway from the center (R-T fingers shown in red in Fig. 2a). These same external zones (2.4-6.0 au) are also rich in Si (Fig. 2b) increasing the likelihood of SiC formation. The median C/Si ratio of the material in this region is ~88, which also indicates efficient formation of graphite or amorphous carbon in the ejecta. On the other hand, the O-rich dust grains are abundantly produced in a spherically symmetric distribution (red ring in Fig. 2c) ~2.4-5.0 au from the center of the explosion, although the production rate of oxygen-rich dust is low in the R-T fingers.

The carbon-rich R-T fingers and some fraction of the oxygen-rich dust are rich in $^{54}$Cr (Fig. 2d), while the ring of material at ~2.7 au (shown inside the yellow circle in Fig. 2e), is largely devoid of this r-process nuclide. The expansion velocities of the carbon-rich ejecta vary from 2400-6100 km/s with a median velocity of 3800 km/s. This material is accelerating rapidly outward with a median acceleration of 2.5 m/s$^2$, while the accelerations of some clumps can be much larger (57.4 m/s$^2$). In contrast, the s-process nuclide $^{50}$Cr is abundant in the interior of the explosion and has a drastically lower range in expansion velocity (1380–2620 km/s) compared to the $^{54}$Cr ejecta. Corroborating evidence is also found in the production of the r-process nuclide $^{50}$Ti in the outer parts of the explosion (and residing in carbon-rich matter) vs the s-process nuclide $^{46}$Ti being primarily produced in the interior (where it condenses into oxides and silicates). Can the differential speeds of the r- and s-process-rich material produce a heterogeneous distribution of these isotopes in a protoplanetary disk, if ejecta from a nearby CCSN explosion interacted with our young, rapidly evolving solar system?

Previous work has shown that a SN must be within ~10 pc for the ejecta to reach our proto-Sun and produce desirable abundances of short-lived radionuclide abundances [e.g., 21]. Owing to their differential speeds, the time-difference between the injection of r- and s-process-rich ejecta can be between 400-2000 years producing a heterogeneous disk. This is much shorter (50-750x) than the time-frames for free-fall and runaway accretion that occur in protoplanetary disks to produce planet-sized embryos (100,000–300,000 years; [22]). We argue that the accretion of only r-process-rich nuclides and participation in CAI formation *requires* an un-mixed distribution of the SN material impinging the disk, which becomes progressively heterogeneous by thermal processing [2]. Some degree of heterogeneity observed in the disk is due to the clumpy nature of SN ejecta [23]. Alternatively, one would require a massive star to go SN ~50 pc from the proto-Sun to trigger solar system formation, which is only likely in a starburst environment. Data on r-process Mo will be presented at the meeting.

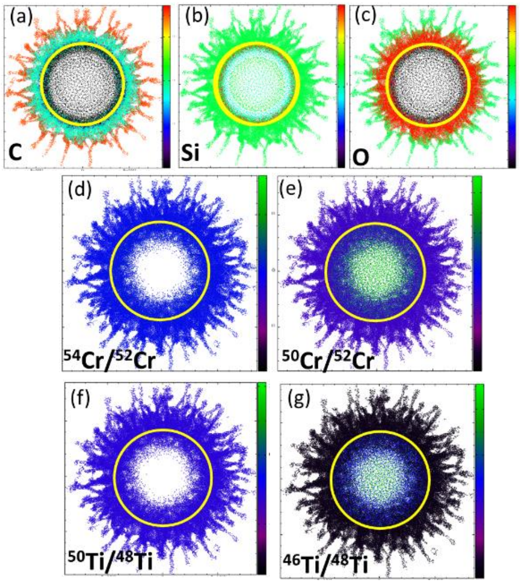

*Figure 2. Mass fraction in the XZ plane of the ejecta from a 3D 15 M⊙ CCSN of (a) carbon, (b) silicon (c) oxygen. Isotope ratios of Cr (d,e) and Ti (f,g) mapped in the same region, show the high abundance of r-process nuclides $^{54}$Cr and $^{50}$Ti in the carbon-rich R-T fingers. Clumps with $^{46}$Ti/$^{48}$Ti >1 trace regions where s-process nuclides are formed, in the interior of the explosion.*

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