FINAL REPORT for NASA GRANT NAG5-10454
Project: History of the Nuclei Important for Cosmochemistry
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1   Stellar Nucleosynthesis and Related Issues

An essential aspect of studying the nuclei important for cosmochemistry is their production in stars. Over the grant period, we have further developed the Clemson/American University of Beirut stellar evolution code. Through use of a biconjugate-gradient matrix solver, we now routinely solve $10^6 \times 10^6$ sparse matrices on our desktop computers. This has allowed us to couple nucleosynthesis and convection fully in the 1-D star, which, in turn, provides better estimates of nuclear yields when the mixing and nuclear burning timescales are comparable. We also have incorporated radiation transport into our 1-D supernova explosion code.

We used the stellar evolution and explosion codes to compute iron abundances in a 25 $M_\odot$ star and compared the results to data from RIMS [5]. Three SiC X grains show higher overabundances of ^{58}Fe than ^{54}Fe, even though their silicon is rich in ^{28}Si. This is surprising since one would typically expect the ^{28}Si-rich region in the supernova to also be ^{54}Fe rich, not ^{58}Fe rich. Moreover, the overabundance ratios (ratios relative to solar abundances) are only $\mathcal{O}(^{54}\mathrm{Fe})/\mathcal{O}(^{56}\mathrm{Fe}) \approx 0.8 - 1.2$ while $\mathcal{O}(^{58}\mathrm{Fe})/\mathcal{O}(^{56}\mathrm{Fe}) \approx 1.3 - 1.8$. These are small numbers given the substantial overabundances of ^{54}Fe and ^{58}Fe relative to ^{56}Fe between the Si-rich and He-rich layers in the star. We argued that these isotopic signatures arise not from condensation but rather from implantation [4]. When the supernova shock encounters circumstellar material, a reverse shock is generated that works its way back into expanding ejecta. The shock slows the supernova gas but the grains, owing to their larger inertia, decelerate more slowly than the gas. This allows the grains, which would have formed deep in the ^{28}Si- and ^{54}Fe-rich matter to rush ahead into the ^{58}Fe-rich layers. As the grains move through the supernova debris, they encounter gas atoms at speeds of ~ 500 km/s. Such impacts can implant the gas atoms to depths of ~ 0.1 μm into the grain. Such encounters would increase the ^{58}Fe richness of the grains but by probably too large a factor. We expect, however, that implantations continue as the grain moves out into the overlying hydrogen envelope and the circumstellar gas, which would have approximately solar composition. From this scenario, we suggest that the trace element abundances in presolar grains from supernovae may reflect implantation processes rather than condensation.

Recently, we have used our own models and those of other workers [28] to argue that the neutron burst that occurs in the helium-shell of a core-collapse supernovae produces enough ^{182}Hf to explain the abundance of that isotope in the early solar nebula if it were injected into the solar cloud along with ^{26}Al, ^{41}Ca, and ^{60}Fe [19, 20]. We were initially skeptical about our model since the amount of ^{60}Fe injected with the ^{182}Hf was too large for the previously preferred value for the initial solar ratio of ^{60}Fe/^{56}Fe of $\sim 4 \times 10^{-9}$ [27]; however, new measurements [24] strongly suggest that the true value is $\sim 1 - 2 \times 10^{-6}$.

Such a value is in excellent agreement with our injection model. Interestingly, the r-process short-lived radioactivities ^{107}Pd, ^{129}I, and ^{182}Hf in our model can all be explained by injection of He-shell material. This may obviate the cosmochemical need for diverse r-process sources for ^{129}I and ^{182}Hf [33], though astronomical evidence still exists for variations in the amount of mass number $A < 140$ and $A > 140$ nuclei ejected in r-process events (e.g., [32]).

In an issue for cosmochemistry related to stellar evolution, collaborator D. D. Clayton, student E. A.-N. Deneault (supported on Clayton's NASA grant), and I modeled the growth of carbon dust in radioactive supernova gas [1]. We ran kinetic models and showed how free oxygen in oxygen-rich environments could favor the formation of large (micron-sized) carbonaceous dust grains. This is of course contrary to results from equilibrium chemistry which would predict that all carbon would be locked up in CO. Mr. Deneault, Prof. Clayton, and PI Meyer have subsequently worked on kinetic networks of this condensation process. In particular, Mr. Deneault used subroutines written by Meyer to model kinetic growth of large carbon grains. This constituted Mr. Deneault's Ph. D. dissertation, which he successfully defended in June 2004.

In our most recent effort, we studied the sensitivity of stellar evolution to the issues of the uncertain ^{12}C$(\alpha, \gamma)^{16}$O rate, the treatment of mixing in chemically inhomogeneous zones in the star, and to the parameterization of mass loss from the stellar surface. This work is in press [6].

2   General Nucleosynthesis

Apart from nucleosynthesis calculations done in the context of our stellar models, we have performed a number of NASA-supported nucleosynthesis calculations based on my one-zone nucleosynthesis network. We demonstrated that the remarkable ^{95,97}Mo excesses found in SiC X grains [26] are most likely due to a neutron burst occurring in the helium shell in core-collapse supernovae [18].

With my one-zone code I also explored r-process nucleosynthesis in matter without excess neutrons. I demonstrated that, contrary to conventional wisdom, it is possible for matter without excess neutrons to make heavy, neutron-rich r-process nuclei [14]. The reason is that for sufficiently rapid expansions of high-entropy matter, a disequilibrium between free nucleons and abundant ^{4}He nuclei give rise to a large neutron-to-seed nucleus ratio even in matter with more protons than neutrons. This nucleosynthesis mechanism turns out to be similar to early-universe nucleosynthesis, and I believe my results point out the fundamental difference between element formation in the Big Bang and in stellar explosive environments. The interesting aspect for cosmochemistry is that r-process yields can be very sensitive to conditions if the environment is near the threshold for this disequilibrium to occur. For example, near the threshold, a $\sim 10\%$ change in the expansion timescale or entropy can take one from an r-process that produces only ^{129}I and no ^{182}Hf to one that produces a considerable amount of ^{182}Hf and almost no ^{129}I. We proposed that this might explain the diverse sources for ^{129}I and ^{182}Hf [16], though we now favor the helium-shell material injection model described above (§1) for understanding the short-lived r-process radioactivities.

With Todd Thompson and Adam Burrows of the University of Arizona, I developed fully relativistic 1-D models of proto-neutron star winds and ran r-process calculations based on the resulting trajectories [31]. We found that only very large (~ 2 $M_\odot$) proto-neutron stars ejected enough neutron-rich matter to produce third-peak r-process isotopes. The mystery surrounding the origin of the heavy r-process elements remains. My own sense is that multi-dimensional effects or magnetic fields, neither yet included in the models, will play a role in producing the right conditions for the r-process.

I also explored the nucleosynthesis of ^{92,94}Mo near the mass cut of a core-collapse supernova. The nucleosynthetic origin of these isotopes remains a mystery. I showed that alpha-rich, neutron-rich freezeouts in the environment outside a proto-neutron star do not produce these isotopes; however, I also showed that, if one includes the effect of the interactions of neutrinos from the cooling proto-neutron star with nuclei during the nucleosynthesis, it is possible to find scenarios in which these nuclei are the most overproduced isotopes [15]. This result will present numerous interesting challenges to supernova models. From the point of view of cosmochemistry, those trajectories that make such large amounts of ^{92,94}Mo also produce large quantities of radioactive ^{92}Nb (mean life of 53 million years). Such large amounts of ^{92}Nb can explain the high inferred initial solar ratio ^{92}Nb/^{93}Nb$\approx 10^{-3}$ [34]. Other determinations of the initial solar ratio have found lower values (e.g, $\sim 10^{-5}$ by [9]). Such lower values would suggest, if the mass-cut site I describe were responsible for the solar system's supply of ^{92,94}Mo, that there was a decay interval between the last events making ^{92}Nb and formation of the solar system. I argued that this is not implausible since the short-lived radioactivity ^{129}I is similarly underabundant and also likely comes from near the supernova mass cut.

More recently, graduate student George C. ("Cal") Jordan and I have followed light p-process nucleus production in fast expansions of proton-rich matter [12, 13]. We showed that such expansions can produce a variety of nucleosynthesis outcomes, including production of light p-process isotopes. We are pursuing this work in light of its implications for cosmochemistry.

Over the last grant period, we also ran reaction-rate sensitivities for alpha-rich freezeouts and prepared a web site for exploring the results [10]. As I write, the web site is moving to a more permanent location, which may be accessed off our new nuclear astrophysics web page:

http://nucleo.ces.clemson.edu/

On this web site one may identify which nuclear reactions govern the synthesis of any particular nuclear yield from an alpha-rich freezeout. The web site also allows an outside researcher to run his/her own nucleosynthesis calculation and vary a given nuclear reaction rate to see the effect. In our study, we found that the reaction ^{57}Ni$(n,p)^{57}$Co was important for the production of ^{57}Co, an important gamma-ray astronomy target, and we have proposed it to nuclear experimentalists for possible study. For cosmochemistry, we are particularly interested in the alpha-rich freezeout since it probably is the dominant producer of the ^{44}Ti that gives rise to the ^{44}Ca excesses in supernova presolar grains. As these grains become better studied and measured, we are likely to find that our attempts to understand their isotopes will be hindered by uncertain reaction rates. In

this way, the grain data and our web site could motivate important new nuclear reaction measurements.

On a topic related to nucleosynthesis, graduate student Sanjib Gupta and I have developed a technique for computing internal equilibration rates for nuclei with long-lived isomers [7]. To date there has been no truly accurate way of treating such nuclei in reaction networks except to take some number of excited states (up to four or more levels!) as separate species. With our technique, we can now treat these nuclei as well as any other species in the network by including only a ground-state and metastable-state ensemble. We have fully implemented this technique in our reaction network and have run calculations for ^{26}Al, our protypical example of such an isotope. We pointed out that a number of isotopes important for cosmochemistry (e.g., ^{26}Al, ^{107}Pd, and ^{182}Hf) are affected by long-lived isomers [22].

3   Chemical Evolution

Chemical evolution was an important aspect of the project supported by the last grant. We made progress in a number of areas. The most significant accomplishment was the development of our web tool for Galactic abundance evolution [21]. On this web site, developed by Clemson student Joel Denny, an outside researcher may calculate his/her own stellar yields, run Galactic abundance evolution, and plot the results. The web site is moving to a more permanent home, which may be reached from our new nuclear astrophysics page cited above.

We have recently been using our chemical evolution models (and especially the web site) to try to understand the dearth of live ^{44}Ti in the interstellar medium [29]. General arguments from the solar system abundances suggest that there should be a significant flux of gamma rays from the decay of ^{44}Ti. This flux is not seen by satellite telescopes. This problem is coupled to the fact that current stellar yields and chemical evolution models fail to produce the solar system's abundance of ^{44}Ca by a factor of roughly two or three (e.g., see Fig. 2 of [25]). This is an important problem in astronomy with implications for our understanding of ^{44}Ca anomalies in presolar grains.

4   Publications arising from the Last Grant

I list below papers and abstracts supported by the NASA Cosmochemistry grant by their number in the reference list. Preprints of the more recent of these papers may be viewed at http://photon.phys.clemson.edu/wwwpages/preprints/meyerpreprints.html

1. Refereed publications:

   - Published: [23, 18, 7, 1, 31, 4, 14, 10]
   - In press: [12, 6]
   - Submitted: [13]
   - In preparation: [29, 17]

2. Other papers and extended abstracts: [21, 2, 16, 3, 19, 15, 20]

3. Other abstracts: [22, 8, 30, 11]

5 Personnel Supported

Mr. Sanjib Gupta was the principal student supported by this NASA Cosmochemistry grant. Mr. Gupta graduated in December 2002 with his PhD and stayed on for six months as a postdoc continuing his work on nuclear isomers. He accepted an offer he has to become a Joint Institute for Nuclear Astrophysics Postdoctoral Fellow at the National Superconducting Cyclotron Laboratory at Michigan State University. This is an excellent position for him and will allow him to continue his nuclear astrophysics work in a prestigous environment.

Upon Mr. Gupta's departure from Clemson, Mr. George C. Jordan, IV became the next student supported on the NASA grant. He has worked on fast expansions of proton-rich matter, which he showed could produce light p-process nuclei [12, 13]. He is following this work up with studies of the implications of this for extinct $^{92}Nb_g$ and p-process molybdenum in grains. Mr. Jordan successfully defended his Ph.D. dissertation in July 2004 and will graduate in August 2004. He will stay on at Clemson for a six-month postdoc before moving on to his next appointment.

Mr. Joel Denny was also supported in part on the NASA grant. Mr. Denny initially worked on the chemical evolution web site as an undergraduate physics major at Clemson. He has since graduated and entered the computer science department at Clemson; nevertheless, he has continued his chemical evolution work part time over the past year, and we have benefitted from his experience and his software engineering knowledge.

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