ACCELERATOR SIMULATION OF ASTROPHYSICAL PROCESSES

T. A. Tombrello
W. K. Kellogg Radiation Laboratory
California Institute of Technology, Pasadena, California 91125

Abstract

The interaction of energetic ions with matter is responsible for many of the processes by which the elements were synthesized, energy is generated in stars, interstellar grains are destroyed, and molecules are created in space. All of these processes are amenable to simulation in the laboratory using accelerated ion beams, which allows us a more comprehensive understanding of Nature than we could obtain by observation alone. In addition, ion beam techniques are extremely useful in the determination of the elemental and isotopic abundances that arise from astrophysical nuclear synthesis.

Introduction

To the best of our knowledge most of the chemical elements were created in the big bang[1] or in the interiors of stars.[2] The nuclear reactions that cause this synthesis also provide the energy that drives most stellar processes, and the accumulated reaction products and the depletion of nuclear fuel species determine the timetable for stellar evolution. The interaction of energetic ions coming from stars (stellar wind, flare particles, and shock waves from explosions) interact with matter in the interstellar medium to produce other elements, to cause the modification or destruction of grains by sputtering, and to generate the hot collisional or implantation chemistry that may be responsible for the creation of simple and complex molecules in space.

We can simulate virtually all of these processes that occur through the interaction of accelerated ions with matter. This simulation provides one of the three sources of information that are essential to obtaining a more complete understanding of Nature. The other two sources upon which we depend are direct observation of astrophysical processes and theoretical models of the astrophysical environment that allow laboratory measurements to be extrapolated to the appropriate conditions. Through the interaction of these three intellectual activities we have made considerable progress; further improvements through laboratory simulation seem particularly promising at the present time.

Synthesis of the Elements

Although the short duration of the big bang precluded the complete production of the heavier elements, the temperatures and densities reached led to the creation of the hydrogen and helium isotopes.[1] The agglomeration of these seed materials into stars produced the sites for further element building. As a cloud of hydrogen and helium collapses, the increasing density and temperature allow the hydrogen burning cycles to occur. The proton-proton chain in smaller or in first generation stars starts with protons and makes ^{4}He through a series of β^{+} decays, radiative capture reactions, and charged particle exothermic reactions.[3] In larger, later generation stars protons are converted to ^{4}He using carbon, nitrogen, and oxygen as nuclear catalysts (CNO cycle). While these reaction cycles are occurring the star stays in hydrostatic equilibrium on the main sequence of the Hertzsprung-Russell diagram. The details of these hydrogen burning reactions have been studied carefully in the laboratory, and although there are difficulties (e.g., the paucity of solar neutrinos[4]), there are few open questions.[3]

When the hydrogen is exhausted in the core of a star, the gravitational contraction resumes until ^{4}He can be burned by nuclear reactions. The time scale is shortened by the high temperature and pressure at which the helium is consumed by alpha particle radiative capture reactions. The laboratory measurements for this stellar regime are fairly complete,[3] but the next stages of stellar evolution are less well defined. This is a consequence of the rapidly increasing temperature and density in the evolving star, which makes an enormous number of reactions possible. For the initial stages the nuclear reactions can be studied in the laboratory, but further evolution causes a further shortening of the time scale so that nuclear excited states and radioactive nuclei can take part in nuclear reactions.[5] Thus, one makes use of theoretical models to bridge the gaps between reactions that are convenient for simulation.[6] It is now clear that the next frontier for laboratory experiments are the reactions involving short lived beams or targets like ^{13}N$(p,\gamma)^{14}$O, ^{15}O$(\alpha,\gamma)^{19}$Ne, and ^{14}O$(\alpha,p)^{17}$F (ref. 7).

At some point during this stage of rapid evolution the nuclear burning can become explosive, leading to a supernova. Much of the current effort in theory is involved in trying to determine more accurately the conditions under which this occurs and what remnant is left after the explosion — white dwarf, neutron star, or black hole.[8] The explosion expels into space the nuclear products of the star's evolution, where they become the material out of which younger stars form. Thus, the "universal" elemental abundances we observe are the result of considerable previous processing.

In addition to the reactions that take place inside stars, some of the elements seem to have been made by the interaction of high energy particles (like cosmic rays) with matter in the interstellar medium. Such reactions are thought to be responsible for the synthesis of ^{6}Li, ^{9}Be, and ^{10,11}B, which are too easily destroyed by (p,α) reactions in stars to have been created there.[9]

It is sufficiently well known how nuclear reaction measurements in the laboratory can be extrapolated to energies appropriate to stellar environments[10] that I shall not discuss it here — preferring to concentrate on newer areas of simulation.

Elemental Abundances

Much of our knowledge of elemental abundances comes from the observations of lines in stellar spectra corresponding to atomic transitions. Until recently the absolute strengths of these transitions could not be determined reliably with standard spectroscopic techniques. An elegant solution was provided by the use of beam-foil techniques to measure the lifetimes of the atomic states, the inverses of which give the required transition strengths. In these measurements an accelerated beam of ions of an element is passed through a thin foil; the lifetimes of the resulting population of excited atoms and ions are determined from the distance they travel before decaying.[11]

Although many elemental abundances have been determined by mass spectroscopy of meteoritic samples, several cases have been done best by nuclear reaction techniques. For example, Goldberg et al., used the ^{19}F$(p,\alpha\gamma)^{16}$O reaction at the 872 keV resonance to determine the fluorine concentration in a number of homogenized samples from carbonaceous chondritic meteorites.[12] Meteorites of this type are thought to

0018-9499/83/0400-1169$01.00

Table 1

Fluorine concentrations for homogenized samples from carbonaceous chondritic meteorites obtained with the $^{19}F(p,\alpha\gamma)^{16}O$ reaction at the 872 keV resonance. These data were taken from ref. 12 and have a typical precision of ± 8%.

Meteorite	Type	Fluorine Concentration (ppm)	Fluorine Concentration (F atoms/10^6 Si atoms)
Ivuna	C1	70	981
Orgueil	C1	74	1037
Murchison	C2	65	739
Mighei	C2	66	751
Essebi	C2	80	910
Haripura	C2	59	671
Allende	C3	59	559

be condensates from the cooling solar nebula that have undergone little subsequent modification; thus, they are expected to represent accurately the abundances of non-volatile elements at the time of solar system formation. The data shown in table 1 give fluorine concentrations for three classes of carbonaceous chondrites; classes C1 through C3 are thought to involve increasing amounts of post-condensation geological processing.

The measurement of isotopic ratios can place stringent constraints on the synthesis mechanisms invoked by astrophysical theories. Usually, only the mass spectroscopists can provide adequate precision, but for the very light elements thermal fractionation in the ion source of the spectrometer can cause serious inaccuracies. The lithium isotopes are an excellent example where a nuclear technique employing the $^6Li(d,\alpha)^4He$ and $^7Li(d,\alpha)^5He$ reactions was used successfully.[13] The lithium was extracted from the material by conventional cation exchange techniques, and the targets were prepared on metal backings from the resulting $LiClO_4$. An alpha particle energy spectrum is shown in figure 1 for the lithium extracted from a terrestrial rock. The lithium isotopic ratios for several meteorites are given in table 2. These ratios are very close to those observed in terrestrial samples.

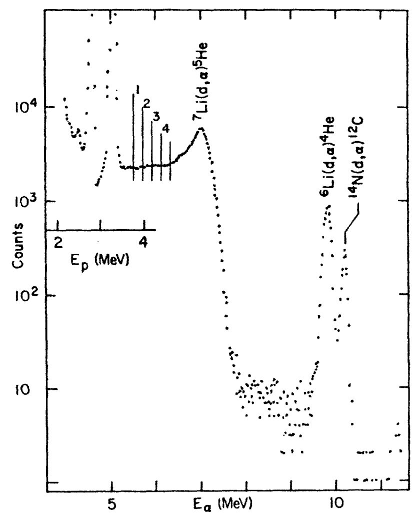

Figure 1. The charged particle spectrum from a $LiClO_4$ target (extracted from a terrestrial rock) under bombardment by a 1.37 MeV deuteron beam. The nitrogen reaction comes from a contaminant; the proton and alpha particles have different energy scales because of a mylar foil in front of the surface barrier detector.[13]

Table 2

Lithium isotopic composition in some stone meteorites. These data from ref. 13 were obtained with the $^{6,7}Li(d,\alpha)$ reactions at a deuteron bombarding energy of 1.37 MeV.

Meteorite	Type	$^7Li/^6Li$
Holbrook	L6-chondrite	11.94 ± .08
Weston	H4-chondrite	12.06 ± .07
Allende	C3-chondrite	11.98 ± .12
Murray	C2-chondrite	12.08 ± .12
Kapoeta	howardite	12.10 ± .07
Malvern	howardite	12.08 ± .06

Sputtering of Planetary Materials

The impact of a low energy ion on a material can result in a billiard ball collision cascade of atoms in the material that often leads to the ejection of atoms from the surface. This process is called sputtering and it occurs in many places in the solar system where there is a high flux of solar wind ions or ions trapped in a planetary magnetosphere.

Recently there has been special interest in the interaction of ions in Saturn's magnetosphere with the surfaces of the small H_2O ice covered moons and ring particles. The ejected material from such sputtering is probably responsible for the toroidal clouds of hydrogen and oxygen that are observed in orbit around Saturn. In order to calculate such effects quantitatively, measurements of the sputtering yields are necessary. The data of Brown et al., shown in figure 2 for the sputtering yield (per incident ion) for frozen H_2O were obtained by freezing water vapor onto a 10^oK substrate.[14] The thickness of the target was measured by Rutherford backscattering before and after the sputtering bombardment. Similar data have been obtained for the frozen SO_2 that is on the surface of Jupiter's moon Io.[15]

Sputtering can also produce changes in isotopic ratios that might mimic those from nuclear reactions. Recently a number of anomalous isotopic distributions have been observed in some of the oldest meteorites.[16] Some of these anomalous patterns are due to short lived radioactive parents that decayed after incorporation into the meteorite. There have been attempts to explain these observations in terms of material produced in a supernova that was injected into the condensing solar system. Many of the isotopic anomalies, however, show no clear pattern that can be definitely traced to this origin.[16]

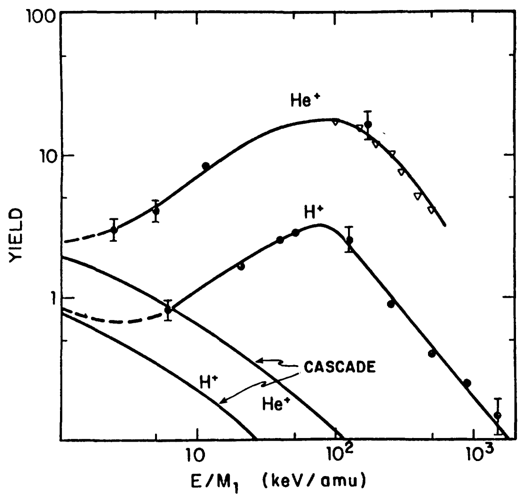

Figure 2. The sputtering yields of H_2O molecules per incident ion for bombardment of a 10^oK H_2O target by protons and alpha particles. The smooth curves are intended only to guide the eye; the curves labeled "cascade" are calculations of that part of the sputtering due to the nuclear component of the ion's stopping power.[14]

It has been demonstrated in simulation experiments that calcium sputtered from mineral targets showed isotopic fractionation.[17] These data can be explained by a theoretical model that also predicts how meteoritic materials would be affected.[18,19] The patterns calculated for melilite ($Ca_2MgSi_2O_7$) are shown in figure 3. The fractionation (δ) and the deviation (ξ) of a linear extrapolation from the lightest isotopes are presented. The anomalies (deviations from linear fractionation) are comparable to those typically observed in meteorites for Si, somewhat smaller than those observed for O and Mg, and much smaller than the Ca observations.

Sputtering of grains would certainly have occurred in the evolving solar nebula, and it is even more likely that shock waves from a supernova would have sputtered grains in the interstellar medium. It is, therefore, especially important to make careful laboratory measurements of isotopic fractionation from sputtering in order to understand the conditions under which such effects can arise and to be able to separate them from the effects of nuclear reactions.

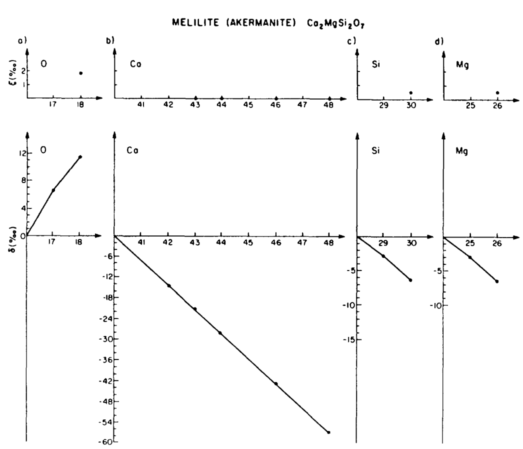

Figure 3. The lower panels (a), (b), (c), and (d) show the fractionation (δ) for O, Ca, Si, and Mg, respectively, for melilite ($Ca_2MgSi_2O_7$). The upper panels in each case show the deviations of the fractionation from linearity. These results from ref. 19 are given in parts per thousand (o/oo).

Synthesis of Molecules

The synthesis of many molecules observed in interstellar space cannot have been the result of binary collisions. Thus, one requires sites where atoms can be collected in order that they have a finite probability for interaction and subsequent combination. The small grains that are observed in space from the extinction of starlight provide just such sites. As discussed in the previous section, if such grains are exposed to stellar winds, then atoms like hydrogen and carbon are constantly striking their surfaces.

In recent simulation studies Bibring et al., have shown that after implantation of carbon and hydrogen ions into SiO_2, molecular bands for CO, CO_2, and hydrocarbons were observed in situ by infrared spectroscopy.[20] The concentrations of molecular products depend on the fluences of the bombarding particles; the molecular bands observed have characteristics that are sufficiently different that they can be distinguished from the corresponding gaseous species.

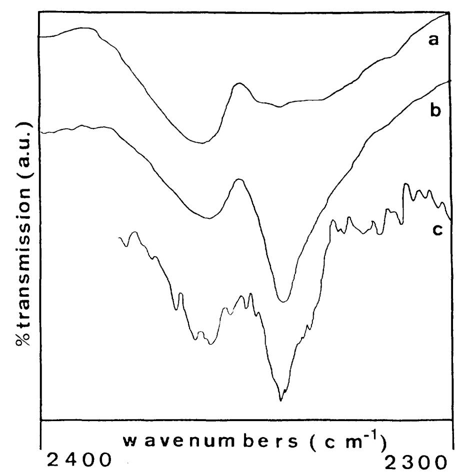

Figure 4. A portion of the IR spectrum of silicate grains from ref. 20. (a) corresponds to unirradiated SiO_2 grains; the double band is from atmospheric CO_2. (b) corresponds to SiO_2 grains irradiated with carbon ions. The single band on the right (superimposed on the double band from atmospheric CO_2) is from synthesized CO_2. (c) corresponds to grains from lunar soil 10084 that were irradiated by the solar wind on the lunar surface. Note the similarity of (c) to (b), which indicates the synthesis of CO_2 by the solar wind.

Figure 4 shows the 2400-2300 cm^{-1} region of the IR spectrum of silicate grains: (a) is for unirradiated SiO_2 grains; (b) is for SiO_2 grains irradiated with ^{12}C ions. The single band of synthesized CO_2 appears as a deep dip on the right side of the double band structure from atmospheric CO_2; (c) is from lunar soil grains (sample 10084 from Apollo 11). The similarity of (c) to (b) shows that CO_2 has been synthesized in these grains by the implantation of solar wind ions.

It is clear that these results represent the very beginning of a particularly exciting field of accelerator based laboratory simulation. Obviously, one would very much like to extend these experiments to see whether more complicated molecules can be made in the same way.

Conclusions

I have tried to list in this talk a number of phenomena that involve accelerated ions, which include the creation of the elements and the synthesis of organic molecules in space. From these examples it is clear that we have an incredibly rich field for exploitation by laboratory simulation experiments. For the most part, the experimental facilities are extremely modest and the experiments are easily feasible for both undergraduate and graduate student projects. But the most important characteristic of this work is the intellectual excitement that comes from duplication in the laboratory those processes that have driven cosmic evolution.

Acknowledgments

This work was supported in part by NASA [NAGW-202 and -148] and the NSF [PHY79-23638].

References

1. R. V. Wagoner, W. A. Fowler, and F. Hoyle, Astrophys. J. 148, 3 (1967).

2. E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Rev. Mod. Phys. 29, 547 (1957).

3. C. A. Barnes, Progress in Particle and Nuclear Physics, ed. D. Wilkinson (Pergamon Press, Oxford, 1981), p. 235.

4. J. N. Bahcall, W. F. Heubner, S. H. Lubow, P. D. Parker, and R. K. Ulrich, Rev. Mod. Phys., in press (1982).

5. D. Bodansky, D. D. Clayton, and W. A. Fowler, Astrophys. J. Suppl. 16, 299 (1968).

6. S. E. Woosley, W. A. Fowler, J. A. Holmes, and B. A. Zimmerman, Atomic and Nuclear Data Tables 22, 371 (1978).

7. R. K. Wallace and S. E. Woosley, Astrophys. J. Suppl. 45, 389 (1981).

8. K. A. Van Riper and J. M. Lattimer, Astrophys. J. 249, 270 (1981).

9. S. M. Austin, Prog. Part. Nucl. Phys. 40, 14 (1980); B. G. Glagola, V. E. Viola, H. Brener, N. S. Chant, A. Nadasen, P. G. Roos, S. M. Austin, and G. J. Mathews, Phys. Rev. C25, 34 (1982).

10. W. A. Fowler et al., New Uses for Low-Energy Accelerators (National Academy of Sciences, Washington, D.C., 1968) pp. 5-74.

11. S. Bashkin, Nucl. Instrum. Methods 28, 88 (1964); W. N. Lennard, W. Whaling, J. M. Scalo, and L. Testerman, Astrophys. J. 197, 517 (1975).

12. R. M. Goldberg, D. S. Burnett, T. A. Tombrello, and M. J. Furst, Meteoritics 9, 347 (1974); T. A. Tombrello, Nucl. Instrum. Methods 168, 459 (1980).

13. R. S. Rajan, L. Brown, D. J. Whitford, R. B. Roberts, and F. Tera, Lunar and Planetary Science IX (Lunar and Planetary Institute, Houston, 1978) p. 925.

14. W. L. Brown, L. J. Lanzerotti, J. M. Poate, and W. M. Augustyniak, Phys. Rev. Lett. 40, 1027 (1978).

15. D. J. LePoire, B. H. Cooper, C. L. Melcher, and T. A. Tombrello, Lunar and Planetary Science XIII (Lunar and Planetary Institute, Houston, 1982) p. 433.

16. T. Lee, Rev. Geophys. Space Phys. 17, 1591 (1979).

17. W. A. Russell, D. A. Papanastassiou, and T. A. Tombrello, Radiat. Eff. 52, 41 (1980).

18. C. C. Watson and P. K. Haff, J. Appl. Phys. 51, 691 (1980).

19. P. K. Haff, C. C. Watson, and T. A. Tombrello, J. Geophys. Res. 86, 9553 (1981).

20. J. P. Bibring, Y. Langevin, and F. Rocard, Proceedings of the Thirteenth Lunar and Planetary Science Conference (Pergamon Press, NY, in press, 1982).