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R–Process Nucleosynthesis in Supernovae

The heaviest elements are made only in cataclysmic events. Finding out whether supernovae are cataclysmic enough requires extensive astronomical observation and sophisticated computer modeling.

John J. Cowan and Friedrich–Karl Thielemann

Almost all of the hydrogen and helium in the cosmos, along with some of the lithium, was created in the first three minutes after the Big Bang. Two more light elements, beryllium and boron, are synthesized in interstellar space by collisions between cosmic rays and gas nuclei. All of the other elements in nature are formed by nuclear reactions inside stars.

Over the 14–billion–year history of the universe, elements made in stars have been ejected back into space to be incorporated into new stars and planets. Thus there is an intricate relationship between the life cycles of stars and the nucleosynthesis of the elements. Fusion reactions inside stellar cores are exothermic. They release the energy that powers stars and supports them against gravitational contraction. During most of a star's life, the principal fusion process is the burning of H to form He.

But binding energy per nucleon increases with nuclear mass only up to iron–56, the most tightly bound of all nuclei. The production of any heavier nucleus by direct fusion is endothermic. Another impediment to the production of heavy nuclei in stars is the growth of the Coulomb barrier with increasing proton number Z. At sufficiently high Z, the Coulomb barrier prevents all nuclear reactions induced by charged particles at stellar temperatures. Therefore, the isotopes of elements beyond Fe are almost exclusively formed in neutron–capture processes. The products are referred to as n–capture elements.

The two main n–capture processes for astrophysical nucleosynthesis were originally identified in 1957 in pioneering work by Margaret and Geoffrey Burbidge, William Fowler, Fred Hoyle, and Alistair Cameron.[1] They are called the slow (s) and rapid (r) n–capture processes. After a nucleus has captured a neutron to become a heavier nucleus, the time scale τ_n for it to capture an additional neutron is either slow or rapid on the competing time scale τ_β for it to undergo beta decay. Whereas τ_β, the mean beta–decay lifetime, depends only on the nuclear species, τ_n depends crucially on the ambient neutron flux.

When a stable nucleus has captured enough neutrons to leave the valley of stability, it becomes unstable. Eventually it undergoes beta decay, which transforms a neutron into a proton and thus increases the nucleus's Z by 1 without changing its mass number A. In the s–process, τ_n is much longer than τ_β. Therefore, a single n capture is almost inevitably followed by beta decay, and the path to increasingly heavy nuclear species charted by successive n

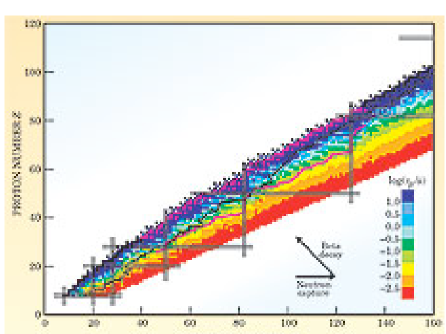

Figure 1

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captures remains close to the valley of beta stability in figure 1. The figure shows how beta–decay lifetimes decrease for a given Z as the increasing neutron number N carries a nucleus away from the valley of stability.

Isotopes involved in s–process nucleosynthesis are, in general, sufficiently long lived to be studied in the laboratory. That is not so for the r–process, in which a sufficient flux of neutrons makes τ_n much shorter than τ_β. In that case, n captures will proceed into the very neutron–rich and unstable regions far from the beta–stable valley. Such high neutron fluxes are only transient—coming, for example, from a supernova explosion. Once the flux is exhausted, the unstable nuclei produced by the r–process will beta–decay back to the valley of stability to form the so–called stable r–process nuclei. Because the r–process path (shown by the magenta line in figure 1) wanders through regions so neutron–rich and so far from stability, experimental measurement of the properties of nuclei along the way is very difficult.

The r–process and the s–process contribute roughly equally to the nucleosynthesis of heavy isotopes. The elements that compose the materials of the solar system contain admixtures from both—but, interestingly, nothing that would appear to be from any astrophysical process intermediate between the two. Some of the n–capture elements are produced by both processes, but some come almost exclusively from one process or the other. All the n–capture elements are rare by the standards of the lighter elements. But those you find at the jeweler's—gold, platinum, and silver—originate almost entirely in the r–process.

The basic ideas of how the r–process operates have been known for some time. But the specific physical conditions and nuclear properties required for the process, and particularly its astrophysical sites, have not been unambiguously identified.[2,3] The s–process is much better known. Its primary sites are low—or intermediate–mass stars (from about 0.8 to 8 solar masses [$M_\odot$]) with long evolutionary time scales measured in billions of years.[4]

By contrast, stars heavier than about 8 $M_\odot$ live only a few million years. They are thought to end up as core–collapse (type II) supernovae when their thermonuclear fusion fuel is exhausted. The products of the s–process take longer to be produced and ejected into the galaxy. That is, they arrive later in galactic history than the r–process elements.[5]

The density of free neutrons required for the r–process points to explosive environments. Supernovae have long been the prime suspects. The earliest studies[1] suggested that the edge of the collapsing core of a type II supernova, ejecting a rich flux of neutrons, might be the site of the r–process. But many difficulties arise in actually confirming the supernova connection. Not enough is known about the detailed physics— for example, the explosion mechanism, the role of neutrino interactions in the explosion, the treatment of hydrodynamic instabilities in three–dimensional simulations, and the equation of state of ultradense matter—required to create realistic supernova models that actually yield explosions. Furthermore, imprecise nuclear data are lacking on the very unstable nuclei involved in the r–process.

The situation has, however, been improving rapidly. There are new high–resolution abundance observations of n–capture elements in halo stars that surround the galactic disk. Models of core–collapse supernovae are becoming more sophisticated, and increasingly reliable data are becoming available on the physics of neutron–rich nuclei far from the valley of stability.

Nuclear properties and the r–process

High neutron densities lead to rapid n capture. But in supernovae, these neutron fluxes are accompanied by high temperatures that produce large quantities of high–energy gammas that instigate nuclear photodisintegration. That process, the reverse of n capture, ejects neutrons from the nucleus. In such an extreme environment, the timescales for both of these competing reactions is much shorter than τ_β. Therefore, the two inverse reactions

$$n + (Z, A) \leftrightarrow (Z, A + 1) + \gamma$$

can come to an equilibrium balance.

This balance between n capture and photodisintegration governs the equilibrium distribution of isotope abundances for a given *Z*. The maximum abundance along an isotope chain is determined by the temperature and the neutron density. The maximum occurs at a specific neutron separation energy S_n, the energy released in a neutron capture. At a given temperature and neutron density, the abundance—maximum value of S_n is the same for all isotope chains, irrespective of *Z*. The r–process path in the *NZ*–plane is then determined; it connects the maximum–abundance isotopes of all the isotopic chains. Beta decay

$$(Z, A) \rightarrow (Z+1, A) + e^- + \nu_e$$

transfers nuclei from one isotopic chain to the next and determines the speed with which heavy nuclei are formed.

The thin magenta line traversing the nuclide chart of figure 1 illustrates an r–process path with S_n between 2 and 3 MeV. Such a path requires a synthesis time on the order of seconds to form the heaviest elements, such as thorium, uranium, and plutonium. During an r–process event, temperature and neutron density—and therefore the path's S_n—change with time. Thus, very unstable nuclei with neutron separation energies ranging from about 4 MeV all the way down to zero can be involved in the r–process. The condition $S_n = 0$ defines the so–called neutron drip line, at which nuclei become unstable to neutron emission.

When the intense neutron flux ends, a nucleus on the r–process path will beta decay back up to the valley of stability and produce one of the stable nuclei indicated by the magenta boxes in the figure. For example, the stable r–process nucleus platinum–198 is originally formed as an unstable lower—*Z* nucleus of the same *A* but with more neutrons. A sequence of beta decays then converts it to $^{198}_{78}$Pt.

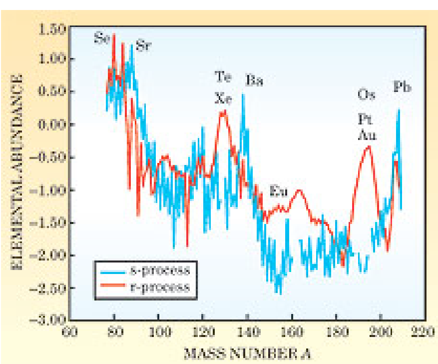


Figure 2

The peaks in the abundance distribution of r–process elements, shown in figure 2, are due to particularly long beta–decay half–lives at "magic numbers" *N* = 2, 8, 20, 28, 50, 82, and 126, corresponding to closed neutron shells. In figure 1, closed neutron and proton shells are indicated by double lines. At the magic neutron numbers, the r–process path, which connects nuclei with the same S_n for different Z, moves closest to the valley of stability. Along the r–process path, nuclei that have the longest τ_β (of order 0.3–0.4 s) determine the abundance peaks. Between peaks, the beta–decay lifetimes are typically one or two orders of magnitude shorter.

The flow of the s–process, for which the interval between successive n captures is much longer than τ_β, is determined by τ_n. The s–process peaks, also shown in figure 2, are due to minima in the n–capture cross–section at the magic neutron numbers *N*. But because the s–process paths stick much closer to the valley of stability, they encounter the magic neutron numbers at higher values of *Z*. Therefore the s–process peaks in figure 2 are systematically offset to higher atomic masses than the corresponding r–process peaks.

The distance of the r–process paths from the valley of stability underscores why information on the properties of nuclei far from stability is so critical to understanding the process. To first order, the values of S_n determine the r–process path,[2] and the values of τ_β determine the shape of the abundance curve. Individual n–capture cross sections can also play a role, especially during the supernova's "freeze–out" transition, when the neutron flux disappears, temperatures drop, and equilibrium conditions no longer prevail.

Fission will occur during an r–process when neutron–rich nuclei are produced at excitation energies above their fission barriers.[2] Fission determines the heaviest nuclei produced in an r–process, and the fission products contribute to the distribution of lighter nuclei.[2,6] The high neutrino flux released in a supernova explosion also gives rise to nuclear interactions, for example

$$\nu_e + (Z, A) \rightarrow (Z+1, A) + e^-,$$

which has essentially the same effect as beta decay.[7]

Site–independent model calculations[6,8] have successfully replicated the abundances of r–process elements in the solar system with superpositions of r–process paths with neutron separation energies in the range of 1–4 MeV. Such paths are far from the valley of stability, traversing regions of the nuclide chart where nuclear properties are poorly known. Some paths extend all the way out to the neutron drip line. Most of the relevant nuclear species are not currently accessible in the laboratory. But rare–isotope accelerator facilities in planning stages in the US and Germany, and already under construction at the RIKEN facility near Tokyo, should make them available to experimenters in the foreseeable future. Expanded theoretical efforts will also be needed to provide reliable predictions of masses, lifetimes, fission properties, and neutrino interactions.[6,7]

Abundance observations in stars

Much of the new knowledge regarding the formation of the heaviest elements has been gained from high–resolution spectroscopic observations of stars in our galaxy, especially of the so–called halo stars. A star's surface abundance of the various elements reflects the interstellar matter from which the star formed. The halo stars circling the galaxy in highly eccentric orbits are among its very oldest stars. By comparison with the Sun, they have very low Fe abundances. But they do have clear signatures of elements made in the r–process. This indicates that the halo stars were formed before there was much s–processing in the galaxy.

The s–process elements come from low–mass stars that often live for billions of years before they end their lives as white dwarfs. Significant s–process material had not yet been ejected into the interstellar medium when the old halo stars were born. The first generation of high–mass stars that ended their short lives as supernovae produced only r–process material. Their ejecta were incorporated into the matter from which the halo stars formed.

One of the best studied of the halo stars is called CS 22892–052. Its ratio of iron to hydrogen is less than a thousandth that of the Sun. The most recent abundance data[9] for CS 22892–052 are shown in figure 3. Fifty–seven elements have been observed in this star 15 000 light years from us. No other star, except the Sun, has had so many of its elements identified. The detections even include the radioactive element Th, which can be used to measure the ages of halo stars.[9,10]

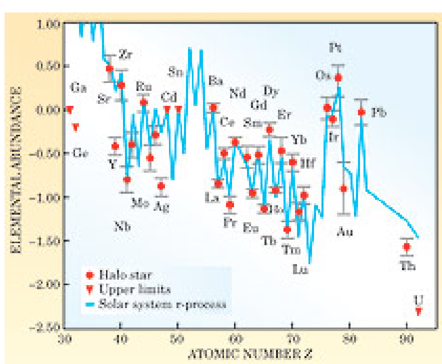


Figure 3

For comparison, a curve of r–process elemental abundances in the solar system is superposed on the CS 22892–052 data in figure 3. Because the s–process can be reliably calculated from nuclear parameters measured in the laboratory, one deduces r–process contributions by subtracting the calculated s–process component from the raw abundance isotope observations. The solar system curve is scaled to compensate for the Sun's enormously greater metallicity—by which astronomers mean the abundance of all elements heavier than boron, but especially iron.

For barium (*Z* = 56) and all heavier elements, there is a striking agreement between the abundances in the halo star and the scaled solar system r–process distribution. The total unscaled abundances are very different, but the relative proportions of the heavy n–capture elements are quite similar in the 4.6–billion–year–old Sun and this much older halo star.

That similarity says much about the r–process. First of all, the presence of these elements in the halo stars demonstrates the operation of the r–process during the earliest epochs of galactic history, presumably in massive stars that ended their lives as supernovae. It also shows that elements normally thought of as s–process products in solar system material, for example Ba, were also formed by the r–process in the earliest galactic times— when the low–mass, long–lived stars that would come to serve as s–process sites had not yet synthesized those elements and injected them into interstellar space.[5]

The agreement between the abundance curves for the heaviest n–capture elements in the halo star and the Sun also demonstrates the robustness of the r–process. The process has clearly been operating in much the same manner over many billions of years. Wherever and however the r–process operates, it appears to be very uniform and well confined in astrophysical parameter space. It seems, for example, that temperature, density, and neutron flux at r–process sites vary only over a very small range. Perhaps that means that only a small minority of type II supernovae, confined to a narrow mass range, produce r–process elements.

Although abundance data for specific isotopes in halo stars are much harder to acquire than the spectroscopic data that provide the elemental abundances of figure 3, recent isotopic observations appear to be in agreement with the elemental abundance trends. In particular, it has been found that the two stable isotopes of europium are found in the same proportion in several old, metal–poor halo stars as they occur in solar system r–process material.[11]

That is not particularly surprising, because Eu is still synthesized overwhelmingly by the r–process. But what about elements like Ba that, unlike Eu, are nowadays primarily made by the s–process? A recent study has found that the relative abundance of different Ba isotopes in one very old halo star is compatible with the Ba isotope ratio attributable to the r–process in solar system material.[12] The Eu and Ba isotope results support the conclusion that only the r–process was producing heavy elements in the early galaxy.

Elemental abundance patterns from additional r–process–rich halo stars now add support to this conclusion.[3] All the stars in this sample have Eu/Fe abundance ratios that typically exceed that of the Sun by at least an order of magnitude. Much less work, however, has been done on r–process–poor halo stars. The halo stars presumably got their heavy elements from material spewed out by supernova explosions of an even earlier generation of massive, short–lived stars. So not all halo stars acquired the same share of these r–process ejecta. In halo stars poor in r–process elements, the heavy elements are much harder to identify spectroscopically. But studies of those very stars might provide important clues about their massive progenitors—the galaxy's first stars.

Figure 3 also shows that the abundances of the lighter n–capture elements, from *Z* = 40–50, generally fall below the r–process curve that fits the heavier elements so well. That difference is suggestive. It might be telling us that the r–process sites for the lighter and heavier n–capture elements are somehow different.[13] Possible alternative sites for the r–process include neutron–star binaries as well as supernovae, or perhaps just different astrophysical conditions in different regions of a single core–collapse supernova.[3] Further complicating the interpretation, strontium, yttrium, and zirconium (*Z* = 38–40) seem to have a very complex synthesis history that raises the specter of multiple r–processes.

Is it always supernovae?

The critical parameter that determines whether the r–process occurs is the number of neutrons per seed nucleus. To synthesize nuclei with A above 200 requires about 150 neutrons per seed nucleus. Iron is generally the lightest of the relevant seed nuclei. Modelers of r–process nucleosynthesis find the entropy of the expanding matter and the overall neutron/proton ratio to be more useful parameters than temperature and neutron density. In a very neutron–rich environment such as a neutron star, the r–process could occur even at low entropy.[8] But even a small excess of neutrons over protons can sustain the r–process if the entropy is high enough.[14]

The question is, Where in nature does one find the appropriate conditions—either very neutron–rich material at low entropies or moderately neutron–rich material at high entropies? But if the entropy is too high, there will be too few seed nuclei to initiate the r–process. The extreme case is the Big Bang, from which ^{4}He was essentially the heaviest surviving nucleus.

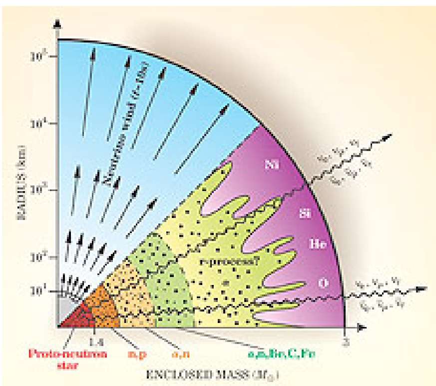


Figure 4

Determining whether r–process conditions can occur inside type II supernovae requires an understanding of the nature of those stellar catastrophes. The most plausible mechanism for such an explosion of a massive star is energy deposition in the star's outer precincts by neutrinos streaming from the hot proto–neutron star formed by the gravitational collapse of the central iron–core when all the fusion fuel is exhausted (see figure 4). The dominant neutrino energy deposition processes are

$$\nu_e + n \rightarrow p + e^- \text{ and } \bar{\nu}_e + p \rightarrow n + e^+.$$

The neutrino heating efficiency depends on convective instabilities and the opacity of the stellar material to the transit of neutrinos. The actual explosion mechanism is still uncertain.[7,14,15] Self–consistent supernova calculations with presently known neutrino physics have not yet produced successful explosions.

There is hope, however, that the neutrino–driven explosion mechanism will prove to be right when the effects of stellar rotation and magnetic fields are included in model calculations that are not restricted to spherical symmetry. There is also still much uncertainty in our knowledge of how neutrinos interact with dense matter (and indeed of how they behave in vacuum). The lack of understanding of the type II supernova explosion mechanism also means that we do not know the exact r–process yields for these supernovae.

The most promising r–process candidate is the so–called neutrino wind: Within seconds of the core collapse and the onset of the shock wave it engenders, a high flux of neutrinos emerging from the contracting core drives surrounding matter outward.[14,15] The high–entropy neutrino wind is expected to lead to a superposition of supernova ejecta with different entropies. If a sufficiently high entropy range is available, one can get the solar system r–process abundance pattern shown in figures 2 and 3.[8,14] However, whether supernova explosions can deliver the very high entropies needed to reproduce those abundances remains to be verified.[15] A galaxy like ours hosts only a few type II supernovae per century. If they are indeed solely responsible for the solar system r–process abundances, each event would have to eject, on average, about $10^{-5}\, M_\odot$ of r–process elements.

Maybe only very massive neutron stars provide the requisite high entropies. Perhaps the inclusion of magnetic field effects or nonstandard neutrino physics can cure the difficulties of the neutrino–wind models. So–called prompt supernova explosion models that don't require waiting for neutrinos have also been explored. They are based on shock propagation from the bounce back after the core collapse to nuclear densities. But those models, with their own problems and uncertainties, have not yet been shown to provide a successful explosion.

Neutron star mergers offer a possible alternative to supernovae as the r–process site. The ejecta from the last seconds of a merger between a neutron star and a compact binary partner (either another neutron star or a black hole) could be so neutron–rich that it would not require high entropies for the r–process to take place.[16] A compact binary pair gradually loses energy by gravitational radiation and tidal interaction over billions of years before its cataclysmic merger. The rate of such mergers in the whole galaxy is, at most, one every 10^4 years. Estimating the ejected mass of neutron–rich matter requires general relativity. But a fully relativistic calculation has not yet been done.[17] The enormous density of free neutrons available in such a scenario (about 10^{33} per cm^3) leads to the buildup of the heaviest elements and also to fission on very short time scales. That, in turn, leads to a recycling of fission products back to the heaviest nuclei via subsequent n captures. However, the resulting calculated composition,[16] which admittedly depends on uncertain fission details, leaves us with no r–process nuclei lighter than about A = 130. It may be that this result is identifying a distinct component of early galactic evolution.

Clues from chemical evolution

Neutron star mergers are much rarer than type II supernovae. And the two processes surely eject different amounts of r–process material into the galaxy. The differences between them enter into the enrichment pattern of r–process elements in galactic chemical evolution. Additional clues to the nature of the r–process and the identification of its primary sites have come from recent studies of chemical evolution.

Figure 5 shows some elemental abundances, normalized to Fe, for three n–capture elements—germanium, zirconium, and europium—in old halo stars and somewhat younger stars in the galaxy's disk, as a function of Fe abundance. The stellar Fe abundances provide a rough timeline. The stars poorest in Fe, such as CS 22892–052, are very old; the more Fe–rich ones, like the Sun, are much younger. The relation is not entirely linear, but it's a useful approximation.

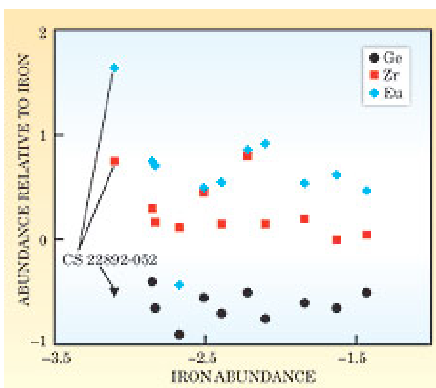
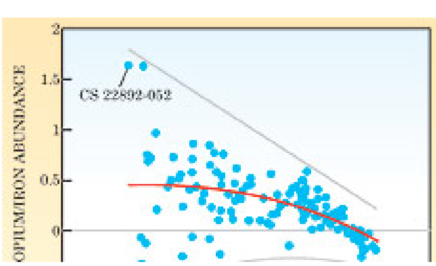


Figure 5

The differences in the evolutionary trends of Ge, Zr, and Eu in figure 5 are striking. Those particular elements make it possible to examine a wide mass range of n–capture elements, from the little studied Ge (Z = 36) to Eu (Z = 63). There is evidence that the lighter and heavier r–process elements might be produced in different environments. In figure 5, the Ge abundance seems to scale linearly with Fe. Germanium appears to be produced in supernovae over a wide range of metallicities and masses. The Ge data points show little scatter. The Zr data show much the same behavior, but with somewhat more scatter.



The Eu data are quite different. They show wide scatter from star to star at early times. Data on Ge abundances are scarce because its dominant atomic transitions are in the UV. But one can examine the Eu abundance trends in more detail. Figure 6 shows the evolution of the Eu/Fe abundance

Figure 6

ratio for more halo and disk stars. The very large star–to–star scatter at early times (low Fe abundances) is immediately apparent, and it diminishes dramatically at higher Fe abundance.

A likely explanation is that the galaxy, at early times, was chemically inhomogeneous, with some regions containing considerably larger amounts of r–process ejecta than others. At later times, these localized inhomogeneities would be smoothed out simply because there were more and more r–process events. There was also more time for r–process products to migrate throughout the galaxy.

Comparing figure 6 with figure 5, which shows very little scatter in the Ge abundances, points out the different production rates of Eu and Ge. It suggests that Ge is made in most, if not all, type II supernovae, but that Eu is made only in a rare subset of them. Zr may be an intermediate case. Thus, the increasing scatter as one goes up in mass from Ge to Zr to Eu may be a statistical consequence of fewer r–process events that produce the heavier elements.

The least–squares fit to the Eu abundance data in figure 6 has several interesting features. First, the ratio of Eu to Fe decreases with increasing Fe abundance. That's mostly due to the galaxy's ever increasing Fe abundance. The primary source of interstellar Fe that goes into the making of new stars is thought to be long–evolving type Ia supernovae.[3] Type Ia explosions have nothing directly to do with the r–process. Rather than being triggered by core collapse in a massive star, they result from the accretion of mass from a binary partner by a white dwarf star not much heavier than the Sun.

Type II supernovae must also have ejected some Fe into the early galaxy. But the nature of those early objects and whether they always synthesize r–process elements along with the Fe is still being studied. Certainly type Ia supernovae are the dominant Fe producers nowadays.

The fitted abundance curve of figure 6 has been satisfactorily reproduced by chemical evolution models that presume core–collapse supernovae to be the primary r–process sites.[18] That success does not exclude the possibility of alternative sites. Some of the type II models suggest that there is an upper progenitor–mass range for the subset of core–collapse supernovae that are actually involved in r–process nucleosynthesis.

We would know better whether there is such a limit that excludes some type II supernovae from the r–process if there were more abundance data at the lowest metallicities. Intensive efforts toward that end are currently under way. Observers are looking for r–process–rich halo stars with even less iron than CS 22892–052. Finding them will reveal whether the Eu/Fe abundance ratio turns down as one looks back to stars with very low metallicities—presumably the galaxy's oldest surviving stars. Indeed, Norbert Christlieb (Hamburg Observatory) and coworkers have recently found a halo star 100 times poorer in Fe than CS 22892–052 that shows no evidence of r–process elements.

Other chemical evolution studies, seeking to compare s—and r–process elemental abundances,[3] are designed to help pin down the sites and galactic histories of both processes. Some of those studies have concluded that, because neutron–star binary timescales are so long, only supernovae could have contributed to r–process synthesis at the earliest times.[18] The very presence of Eu in the old halo stars suggests that the first r–process sites evolved rapidly. The surviving low–metallicity halo stars may be just a few million years younger than the galaxy. So the r–process sites must have lived and died and spewed their output into the primordial interstellar medium before that. Supernovae resulting from the core–collapse of massive, short–lived, first–generation stars fit that scenario better than anything else we know about.

What's next

The study of r–process nucleosynthesis and its connection to supernovae has been extremely fruitful over the past several decades. But there are still important unanswered questions. Answers are now being sought by international collaborations of astronomers and physicists. New initiatives include high–resolution spectroscopic studies of large numbers of galactic halo and disk stars. These observations have been greatly aided by the availability of the *Hubble Space Telescope* and large ground–based telescopes such as Keck, Subaru, and the Very Large Telescope. All these instruments are being used to probe the earliest nucleosynthesis in our galaxy by systematically searching for n–capture abundances in very low–metallicity stars. The new abundance observations impose strong constraints on the theorists.

Ongoing supernova studies relevant to the r–process include efforts to determine the equation of state of extended nuclear matter at densities typical of collapsing stellar cores. The latest supernova models incorporate much of what's been learned in recent years about the subtle behavior of neutrinos. They use multidimensional modeling and sophisticated numerical treatments made possible by faster computers.

Reliable determinations of the properties of the most neutron–rich unstable nuclei are becoming available. These better data are the result of improved nuclear–mass models coupled with new experimental measurements that are steadily working their way into the most radioactive regimes of the nuclide chart.

All this progress brings us closer to a full understanding of the process that makes the heaviest and rarest elements in the universe.

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John Cowan is a professor of physics and astronomy at the University of Oklahoma in Norman. ***Friedrich–Karl Thielemann*** is a professor of physics at the University of Basel in Switzerland.

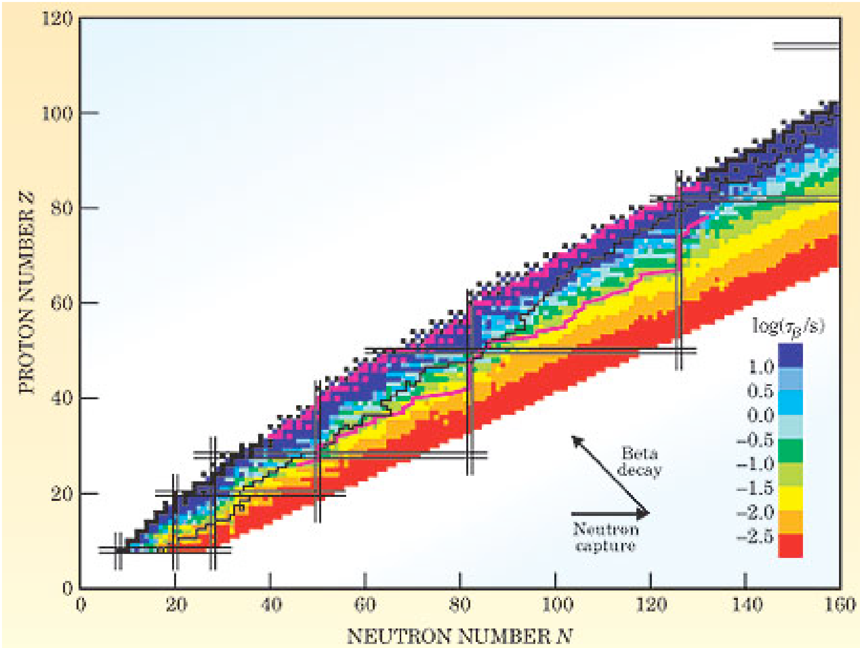

Figure 1. The stable and neutron–rich unstable nuclides.[3] Isotopes stable against beta decay, indicated by black and magenta boxes, form the valley of stability that runs along the top edge of the band. (Proton–rich isotopes on the valley's other side are not shown.) Colored bands indicate decreasing measured or predicted lifetimes τ_β with increasing distance from the valley. The jagged black line is the limit of laboratory information. The jagged magenta line shows a typical path of rapid (r–process) neutron captures. Such paths tend to turn vertical at the double vertical lines that mark neutron numbers corresponding to closed neutron shells. (The horizontal double lines indicate closed proton shells.) A nucleus on an r–process path eventually beta decays up to the valley to become one of the r–process stable nuclei indicated by the magenta squares. (Courtesy of Peter Möller.)

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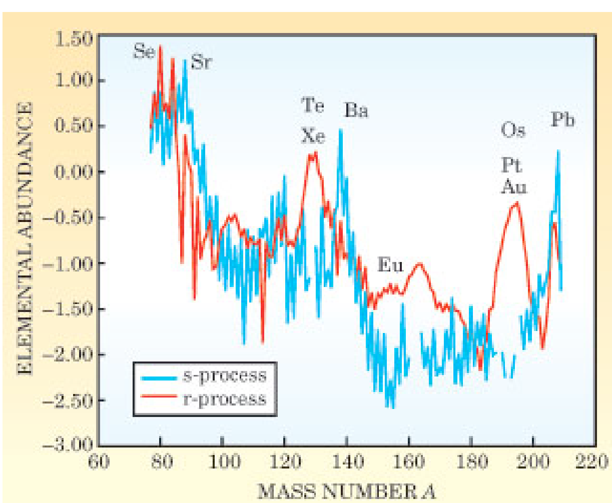

Figure 2. Solar system abundances of heavy elements produced by r–process and slow (s–process) neutron capture. Plotted values are $12 + \log_{10}$ of abundance relative to hydrogen. Abundance peaks are caused by maximum τ_β

or minimal n–capture rates at magic numbers corresponding to full neutron shells. Because the r–process carries nuclei farther from the valley of stability than does the s–process, it encounters each closed shell at slightly lower mass number. Hence the r–process peaks are offset to lower *A*. The curves are not renormalized; the two processes really have contributed about equally to the solar system's inventory of heavy elements. (Adapted from ref. 3.)

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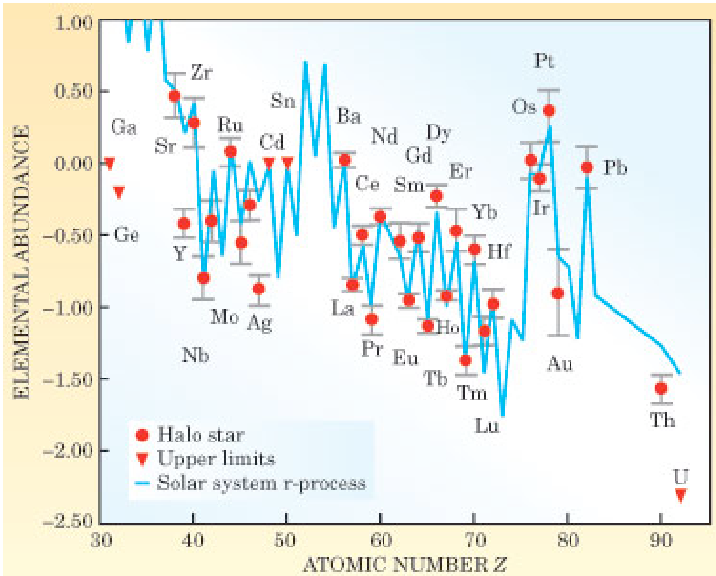

Figure 3. Elemental abundances in the halo star CS 22892–052 are compared with solar system abundances attributable to the r–process. The numerical values of the halo–star abundances follow the convention of figure 2. The solar system r–process abundances are scaled down to compensate for the higher metallicity of the much younger Sun. (Adapted from ref. 9.)

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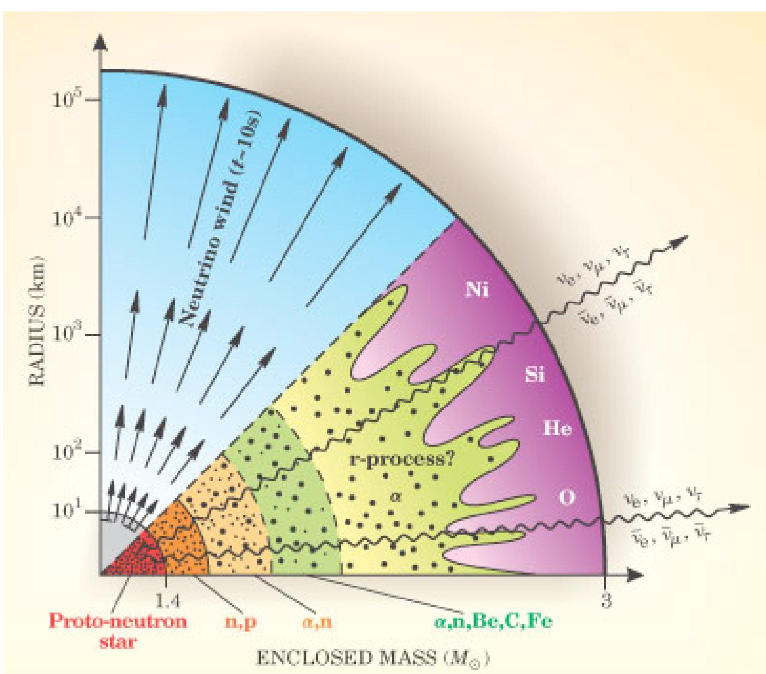

Figure 4. Type II supernovae are triggered by the sudden collapse of the iron core of a star of at least 8 solar masses ($M_\odot$), when the star's

thermonuclear fuel is exhausted. The core collapses to form a proto–neutron star with a mass of about 1.4 $M_\odot$ enclosed within a radius of less than 10 kilometers. Within less than a second, a wind of neutrinos from the collapsing core is presumed to deposit enough energy in the star's outer shells to sustain the explosion triggered by a shock wave from the core collapse. The shock wave subjects the matter outside the core to explosive burning. The matter moves outward and is followed by smaller amounts of material driven by the neutrino wind. In the hottest regions just outside the core, only free nucleons remain. Farther out there are also helium nuclei (a particles). Still farther out are somewhat heavier nuclei that presumably serve as seeds for rapid neutron capture—the r–process. (Courtesy of H. Thomas Janka.)

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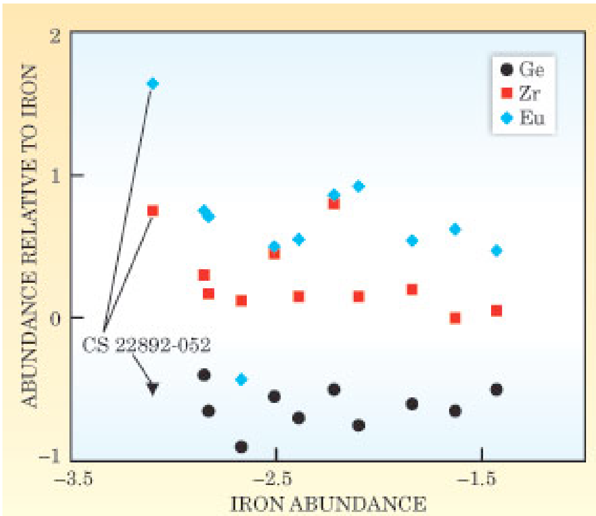

Figure 5. Abundances of neutron–capture elements germanium, zirconium, and europium in old halo stars and younger stars in the Galaxy's disk, plotted as a function of iron abundance, which provide a rough timeline. The halo star CS 22892–052, poorest in Fe, is presumably among the oldest. The triangle is an upper limit. The Eu abundance, showing the widest scatter from star to star at early times, is examined in greater detail in figure 6. (In both figures, n–capture–element abundances are normalized to Fe, and the abscissal Fe abundance is normalized to hydrogen. All numerical values are $\log_{10}$ of the abundance ratio normalized to the corresponding solar ratio.)

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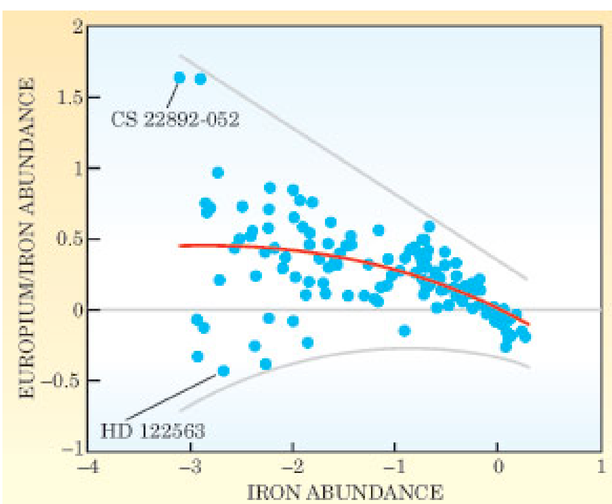

Figure 6. Europium abundance in a large sample of old and young stars, age being inferred from Fe abundance. The halo star HD 122563 is almost as Fe–poor as CS 22892–052, and therefore presumably just about as old, but it has much less Eu, an element made only in the r–process. The red line is a least–square–fit to the data, and the gray flanking curves indicate decreasing scatter in the data with increasing time. Numerical conventions are as in figure 5. Zero on the abscissa means Fe abundance like that of the 4.6–billion–year–old Sun.

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