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NUCLEAR PROCESSES ASSOCIATED WITH PECULIAR A-TYPE STARS*

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A discussion is given of the various roles that both internal and surface nuclear reactions may play in production of anomalous abundances of elements in peculiar A stars.

Key words: peculiar A stars — anomalous abundances

Introduction

There appear to be three major types of process which may play a role in the production of very large abundance anomalies in the surface of peculiar A stars. These include both upward and downward diffusion of elements in the stellar surface layers (Michaud 1970), surface nuclear reactions (Burbidge and Burbidge 1955; Fowler, Burbidge, and Burbidge 1955; Brancazio and Cameron 1967), and internal nuclear reactions (Fowler et al. 1965). It seems to me that all three of these types of process may in fact be important in explaining various features in the entire range of the peculiar A stars. In this paper I shall discuss various effects which may be expected to occur both in the surface nuclear reactions and in some possible internal reactions which can occur in advanced stages of stellar evolution.

Surface Nuclear Reactions

The first attempt to explain peculiar abundances in peculiar A stars by surface nuclear reactions was made by Burbidge and Burbidge (1955), and elaborated by Fowler, Burbidge, and Burbidge (1955). In these papers the authors postulated that reactions, in which alpha particles, deuterons, and neutrons are bombarding particles, may lead to a build-up of heavy elements in the surfaces of stars. These calculations were semiqualitative, in the sense that the authors did not utilize extensive reaction rate networks and precise estimates of reaction cross sections. The later work by Brancazio and Cameron (1967) considered the reactions which could be induced by bombarding protons and alpha particles, and utilized extensive reaction rate networks with quantitatively calculated reaction cross sections. No attempt was made to follow the secondary reactions produced by neutrons and by deuterons, which are formed by neutron capture on hydrogen.

Brancazio and Cameron considered nuclear reactions which could be produced by a power-law spectrum of accelerated particles. The energy spectrum was assumed to vary like E^{-n}, where $n = 2.5$, typical of the spectra produced by cosmic-ray acceleration processes. This spectrum was taken to have a lower cutoff energy of one MeV. Nuclear reactions produced by bombarding protons and alpha particles were calculated over an energy range from one MeV up to about 50 MeV for nearly 300 nuclear species acting as target nuclei. This includes the stable nuclei and also long-lived nuclei near the valley of beta stability. The nuclear cross sections utilized compound nucleus theory together with detailed estimates of the average nuclear properties which enter into compound nucleus theory.

The general character of the results obtained in this approach was very simple. For bombarding protons, the net effect of the power law spectra is the destruction of the target nuclei. At very low bombarding energies, effectively no reactions occur. With bombarding energies of the order of 10 MeV, a proton may enter a nucleus, and either a neutron or a proton may be ejected, and occasionally an alpha particle. These reactions usually leave the mass number

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1971PASP...83..585C

of the target nucleus unchanged. But at higher bombarding energies, the absorption of a proton will usually be followed by the ejection of two or more protons or neutrons. The net effect of these reactions is thus destructive, with the mass number of the target nucleus being decreased. A power-law spectrum of these bombarding energies will thus have a net destructive effect on the bombarded nuclei.

If a nuclear reaction network is utilized to determine the changes in the abundances of the target nuclei, it is readily seen that continued bombardment of any system of target nuclei results in moving each initial nucleus toward lower mass numbers. Very large bombardments can thus deplete the heavier elements in a stellar surface. Only in a very few cases will element abundances be increased by this process, and in these cases this occurs usually for lower integrated bombarding fluxes.

Roughly speaking, higher energy spallation reactions tend to produce roughly equal abundances of the destruction products of the bombardment. An odd-even abundance effect persists, in which even mass numbers may remain a factor of perhaps two more abundant than odd mass numbers. Hence enhanced abundances may appear where there is a very large abundance ratio between adjacent elements. An example of this is the element phosphorus. This is normally about two orders of magnitude less abundant than the neighboring elements silicon and sulfur. Consequently, spallation reactions will break down the sulfur and the phosphorus may become nearly two orders of magnitude overabundant as long as the general abundance level in this region has not yet been seriously depleted. One can also expect an enhancement of scandium and its neighboring elements, since these lie in an abundance valley between calcium and the iron equilibrium peak. It is possible that phosphorus anomalies in peculiar A stars may rise in this way, but then it is surprising that there is not a greater mention of scandium and titanium anomalies.

Another result of proton bombardment will be the destruction of helium, leading to such partial disintegration products as deuterium and helium 3. Since the helium 3 will have a somewhat smaller destruction cross section than helium 4, it is possible to produce an excess of helium 3 over helium 4 if the bombardment has progressed for a long time and has been very thorough over the entire surface of the star. Such an enhancement of helium 3 relative to helium 4 could then only occur provided the total abundance of helium has been considerably reduced. This appears to be the situation in the star 3 Centauri A. However, this star also possesses a greatly enhanced abundance of some heavier elements (Hardorp 1967). Hence the destructive effects of surface proton bombardment are unable to account for all of the features observed in this star.

If the bombarding flux is composed of a stream of pure alpha particles, then the net effect of the bombardment is constructive. Low-energy alpha particles will produce virtually no net result, but alpha particles with energies of the order of 10 MeV may be absorbed by the nucleus, resulting in the emission of a neutron or a proton. The net effect is the increase of the mass number of the nucleus by three units. As the bombarding energy increases, further nucleons may be emitted following the capture of the alpha particle, reducing the gain in mass number. At very high energies, the bombardment leads to destructive reactions, but such high energies receive very little weight in the power-law spectra. Hence the net effect integrated over the power-law spectra is to increase mass numbers.

Brancazio and Cameron found that the light and medium elements would be moved up toward the heavy element region as a result of sustained alpha-particle bombardment. The ultimate effect of such bombardment was to produce an extreme enhancement of the rare-earth elements, with the abundances climbing very rapidly beyond barium. This is indeed one of the major anomalous abundance effects which are often observed in peculiar A stars. However, the overabundance factors which are produced by this process are enormous compared to those observed. It is therefore evident that the process can only operate in very small patches (star spots) on the stellar surface, followed by diffusion away from the production site, if this process is to be invoked to account for rare-earth anomalies in peculiar A stars.

Bombardment by a combined flux of protons

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1971PASP...83..585C

and alpha particles in solar-system proportions has a net destructive effect at all times. This is because the protons are an order of magnitude greater in abundance than the alpha particles, and their cross sections for inducing nuclear reactions are greater. Thus the only way in which a heavy element enhancement can be produced by a surface bombardment process is to selectively accelerate the alpha particles, producing essentially a pure beam of these particles.

D. B. Melrose (private communication, 1967) concluded that it may be possible to accelerate alpha particles selectively provided that certain cyclotron resonance conditions could be attained in a surface magnetic field. However, many different resonances can play a role under different circumstances, and it has not become clear whether there should be any expectation of the dominant operation of the alpha-particle acceleration mode under any realizable conditions. This must continue to be regarded as an open question.

Neither the surface nuclear reactions considered here nor the internal nuclear reactions to be discussed in the following section will produce large-scale selective depletions of certain elements, such as carbon, oxygen, or calcium. The observational evidence for such depletion thus leads me to believe that Michaud's surface diffusion mechanism may be operating. However, in this case it is possible that there will be an upward diffusion of certain elements, such as iron and the rare earths, and hence, such upward diffusion processes may be sufficient to account for many of the overabundance anomalies which are observed in such peculiar A stars as 3 Centauri A. However, the diffusion mechanism would certainly not account for the excess of helium 3 over helium 4 in that star, and hence it is difficult to escape the conclusion that large-scale surface nuclear reactions have been going on.

Internal Nuclear Reactions

In considering whether internal nuclear reactions can lead to abundance anomalies in peculiar A stars, we must consider whether the reactions occur in the interior of the star under consideration, in the interior of a companion star which was disrupted and deposited anomalous distributions of elements on the surface of its companion, or in general galactic nucleosynthesis. I have never been able to take the stellar companion theory seriously, because the abundance anomalies in peculiar A stars are not representative of ordinary nucleosynthesis, and hence we cannot expect the disruption of a star which ejects large quantities of anomalous abundances into space (so that only a small fraction are captured by the companion), to be able to be a very common event in space. The peculiar A stars are very common among the A stars, and hence there would be a quantitative disagreement between the production of elements in solar-system proportions and the production of elements by stellar disruption in the vicinity of peculiar A stars. In addition, any supernova explosion occurring in the companion star would not deposit elements gently on the surface of its companion, but rather the impinging gases from the supernova explosion would sweep away the outer surface layers of the companion star, leaving no net deposition of matter from the supernova ejecta.

An elaborate theory of element production in peculiar A stars has been advanced by Fowler et al. (1965). In this theory the nuclear reactions operative in the interior include rapid neutron capture (the r-process), and rapid helium burning and silicon burning required to manufacture silicon and iron peak elements, as well as surface nuclear reactions in order to account for the anomalous helium 3 in 3 Centauri A. A star must reach an advanced evolutionary stage in order to produce such reactions, and eventually it must be mixed so that it will once again appear on the main sequence.

This theory was criticized by Truran and Cameron (1967), who objected to the rapid helium and silicon burning in the interior required to produce iron peak elements since this would require sufficiently high temperatures to be characteristic of the supernova process, so that the star would be blown apart. It was also criticized by Searle and Sargent (1967), who pointed out that the theory seemed to be in conflict with several observational features: the slow rotation of peculiar A stars, the main-sequence position of peculiar A stars in clusters where more massive ordinary stars are still on the main sequence, and an apparent correlation

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1971PASP...83..585C

of abundance peculiarities with surface convective conditions.

I believe that the recent discovery of isotope anomalies in mercury in pecular A stars by Dworetsky, Ross, and Aller (1970) and by Preston (1971) requires a re-evaluation of this situation. These authors found that the star ι Coronae Borealis had somewhat of an enrichment of the neutron-rich isotopes of mercury relative to the terrestrial composition, that the star HR 4072 had a greater enrichment of the neutron-rich isotopes, and that the star HR 5883 was an extreme case, with mercury 204 having 97 percent of the abundance and mercury 202 the remaining 3 percent. I do not know of any way in which surface nuclear reactions could produce these anomanously large abundances of the neutron-rich isotopes of mercury, since spallation reactions tend to produce neutron-deficient isotopes of heavy elements. It appears that neutrons must be involved in the reactions, but the standard processes of nucleosynthesis will not produce these results, since they have produced the much more even distribution of mercury isotopes characteristic of solar-system abundances. However, mercury produced solely by the r-process would have some enhancement of the heavier isotopes.

Let me discuss the following scenario, which is an extension of a suggestion made by Cameron and Fowler (1971). Imagine an early or middle B star, which evolves off the main sequence and through central helium burning. In the phase in which it has a double helium-burning and hydrogen-burning shell, while it is a red-giant star, an extensive amount of mass may be lost by stellar winds. Helium shell flashes can then occur, leading to a convective helium layer in the star, which may grow sufficiently to start mixing hydrogen toward the base of the helium layer, as has been found by Schwarzschild and Harm (1965, 1967), Weigert (1966), and Rose (1966, 1967). The reaction $C^{12}(p, \gamma)N^{13}(\beta^{+}\nu)C^{13}$ combines the admixed hydrogen with the carbon products of the triple alpha reaction. When the C^{13} is mixed to the region of the helium-burning layer, then $C^{13}(\alpha, n)O^{16}$ can produce a source of neutrons. This reaction will build up the heavy elements by the s-process as long as the characteristic time between neutron captures is of the order of 10^7 seconds, as found by Schwarzschild and Harm. Fowler and I suggested that in somewhat more massive stars than those considered by Schwarzschild and Harm, the degree of admixture of hydrogen may be greater, leading to an energy release by reactions in the helium layer due to the admixed hydrogen in excess of the energy release in the helium shell flash itself. We then suggested that this could lead to a major structural rearrangement in the star, mixing the products of neutron capture throughout the outer envelope, producing red-giant stars of the carbon and S spectral classes. In the present context, let us consider that conditions have become even more violent than this, and the star has mixed completely throughout, thus returning to hydrogen burning in the vicinity of the main sequence.

Would such a mixed star lie as close to the main sequence as observations indicate the peculiar A stars do? Helium would be enriched in such stars, which would tend to increase the luminosity, lifting the star above the ordinary main sequence. However, helium-burning products, such as carbon and oxygen, will also be very plentiful in the star, leading to an increased opacity in the interior, and lowering the luminosity. It seems entirely possible that the net result of these two effects could be to leave the star very close to the ordinary main sequence.

At least two of the objections of Searle and Sargent (1967) need not apply to the production of peculiar A stars in this manner. The mass of the star will be significantly less than its original main-sequence mass, owing to mass loss in the red-giant stage, so that the star may well lie in the vicinity of the main sequence in a cluster at a lower mass position than stars which have not yet evolved off the ordinary main sequence. The loss of mass in the red-giant stage will have carried angular momentum away from the star, so that it would not be surprising for the stars to be slow rotators. I am not very impressed with the remarks of Searle and Sargent concerning the correlation with surface convective properties, and I see no reason why whatever correlation exists might not be entirely accidental.

I invoke this mechanism only for the production of heavy elements in peculiar A stars. I do not see any obvious way in which abundance anomalies such as enhanced iron or manganese

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1971PASP...83..585C

could be produced by such a mechanism. We would still require Michaud's diffusion mechanism to operate to produce these. But the possibility exists that an enhancement of the heavier neutron-rich isotopes of mercury and platinum could be produced in this way.

The ordinary s-process will not produce the enhanced heavy mercury isotopes. Neither will the ordinary r-process produce them, according to studies by Cameron, Delano, and Truran (1970), and also according to more recent studies carried out by these authors relating to this specific problem in peculiar A stars. The r-process tends to produce a more or less level run of abundances in the platinum and mercury region.

However, an enhancement of the heavy mercuries may be produced by neutron capture on an intermediate time scale. Suppose during the later stages of the thermal runaway which produces neutrons in the helium-burning layer of of the postulated star, just prior to its mixing, that the mean time between neutron captures on a typical heavy nucleus is reduced to about one hour. The capture path for the nuclei then moves to the neutron-rich side of the valley of beta stability. A simplified section of a nuclide chart containing the platinum and mercury region is shown in Figure 1. In this figure, the neutron numbers are plotted on the abscissa and the proton numbers on the ordinate. The squares outlined with heavy black borders are stable against beta decay and are the ones which exist in nature. These nuclei are shown with their mass numbers and their relative isotopic abundances. The nuclei with light borders are

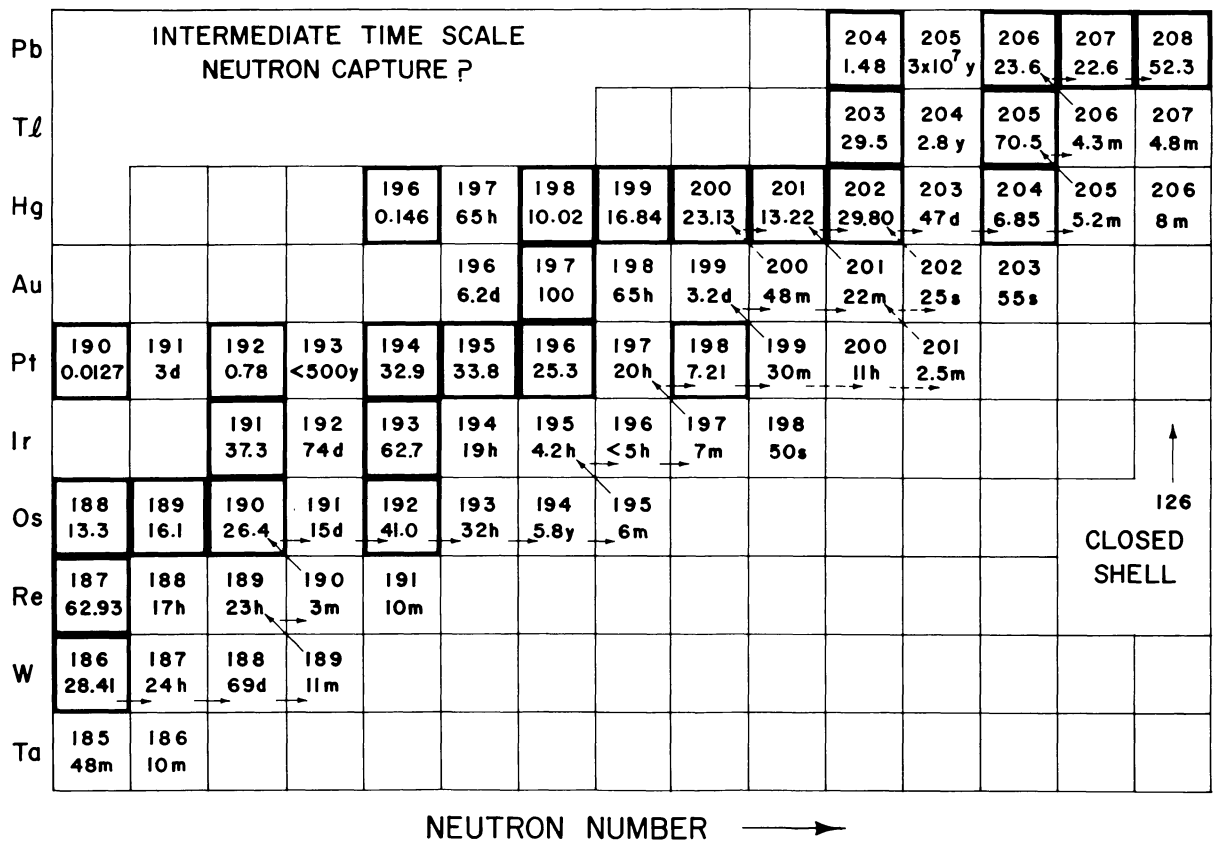

FIG. 1 — A simplified portion of a nuclide chart containing the region of platinum and mercury. Each square represents a nucleus; the squares with heavy borders are beta stable nuclei. The upper figure in these squares is the mass number, and the lower figure is the isotopic abundance in percent. The squares with thin borders are beta unstable; the upper figure in these squares is the mass number, and the lower figure is the beta decay half-life. The solid arrows show the neutron capture path under circumstances in which the mean life between neutron captures in heavy nuclei is about one hour; the dashed arrows show some cases of expected branching.

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1971PASP...83..585C

unstable against beta decay; they are shown with their mass numbers and their half-lives. The arrows on this chart show the capture path which would exist corresponding to a mean time between neutron captures of about one hour. In a few places weak branches of the capture path are shown, where the beta decay lifetime is also in the general vicinity of one hour.

In ordinary nucleosynthesis an r-process peak is centered at platinum at mass number 195, accounting for the large isotopic abundance of this isotope in Figure 1. Under the capture conditions postulated here, mass number 195 would be considerably lower in abundance than 194 and 196, owing to the odd-even effect. The half-life of irridium 196 is less than five hours, and the arrow in Figure 1 has been drawn to the right of this nucleus on the assumption that the half-life is greater than one hour. Capture in such a nucleus with an odd-proton number and an odd-neutron number involves a much larger cross section than capture in an even-even nucleus, and hence this will lead to a depressed abundance at mass number 196. Under these circumstances, it is easily possible that about 40 percent of the abundance of platinum may reside in mass number 198.

In the case of the mercury isotopes, the abundance of mass number 200 may be depressed because a significant fraction of the capture path can go through gold 200, which is also an odd-odd nucleus. However, perhaps the most significant feature is that the capture path goes through mercury 204. This contains 124 neutrons, only two less than the closed shell at 126 neutrons. It is known that neutron-capture cross sections decrease markedly in the vicinity of closed neutron shells, and I would expect that the capture cross section on mercury 204 would be very much less than the capture cross section of mercury 202. Hence it appears possible that this intermediate-time-scale neutron capture may account qualitatively for the appearance of enhanced abundances of the neutron-rich isotopes of platinum and mercury in the manganese sequence of the peculiar A stars. I believe that this scenario thus can profit from a more quantitative examination than has been given in the above remarks.

Such a quantitative examination must be concerned with more than just the details of the nuclear reactions which are involved. It is also necessary to determine how the star can be completely mixed by thermal runaways to temperatures of the order of $4 \times 10^{8\circ}$ K in the helium-burning shell in the above scenario, which is required to produce the indicated rapid rate of neutron capture. Rapid burning in the shell can only be expected to lead to mixing throughout the outer envelope, leaving a degenerate core and a red-giant structure. In order to expand the core, nuclear reactions must also occur at a significant rate in the interior of the core. It is possible that raising the peripheral temperature of the core to temperatures in the vicinity of $4 \times 10^{8\circ}$ K may cause interior nuclear reactions to generate enough energy to expand the core and lead to complete mixing. In this regard, it should be noted that a helium-burning shell possesses a very wide tail of reactions going deep into the interior, since the exhaustion of the last few percent of the helium is a very slow process. Presumably this residual helium would have to be heated, leading to temperatures in the core of order $6 \times 10^{8\circ}$ K, in order to initiate carbon burning at the periphery of the core in a nonexplosive manner, leading to an inward propagation of a brief phase of carbon burning, which can release enough energy to mix up the star.

This scenario may also have far reaching consequences for nucleosynthesis itself. It may be seen in Figure 1 that all of the isobars which are customarily produced in the r-process are also produced by this intermediate process. In the present scenario quite large abundances of these neutron-capture-produced heavy elements would be produced, and hence we would have to expect that this process has made a contribution to the r-process nuclei in nature. Not all of the observed r-process nuclei can be produced in this way, since the distinctive closed-shell-associated peaks such as that at platinum 195 would not be produced in this way. Nevertheless, this may well complicate the interpretation of r-process abundances and the understanding of the site of the r-process in nature.

There is one very important way in which the above scenario is very incomplete. The intermediate-time-scale neutron capture would

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produce comparable amounts of mercury, platinum, and the rare-earth elements. But the rare-earth elements are much less abundant than mercury in ι CrB. Thus we must again invoke a selective diffusion process to enhance mercury relative to the rare earths. Once again we must invoke Michaud's process. This means that the only evidence for the above scenario lies in the anomalous isotopic abundances of the mercury.

If Dworetsky, Ross, and Aller should be mistaken about the extreme mercury 204 enrichment in HR 5883, then the above scenario might be unnecessary. Much milder enhancements of the heavy mercuries would occur if peculiar A stars are now made from an interstellar medium in which there is a much larger ratio of r-process products to s-process products. Alternatively, perhaps the intermediate-neutron-capture time scale process occurs, not as in precisely the above scenario, but in an astrophysical environment which now makes a much larger contribution to galactic nucleosynthesis than at the time of formation of the solar system. In this case stars like ι CrB, HR 4072, and HR 5883 would be formed with their enrichment of the heavy mercury isotopes. This alternative would also have immense significance for nucleosynthesis theory. But in any case we would always have to invoke the Michaud diffusion process to account for the large surface abundances of mercury.

Discussion

In the foregoing we have seen that various features of peculiar A stars may require the operation of two or more of the processes of surface diffusion, surface nuclear reactions, and internal nuclear reactions. If this is correct, then the untangling of these various effects will be a delicate task, and will require extensive abundance determinations of a very wide range of elements. In this connection, it should be noted that a clear astrophysical understanding of the situation will require not only a determination of the abundances of elements which are greatly overabundant, but also a knowledge of which elements have normal abundance, and which ones have abundance deficiencies. The recent progress in abundance determinations is very encouraging in this respect, and I hope that it will be possible to understand the role of various types of nuclear reactions in peculiar A stars much better in the next few years.

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