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Astronomical Evidence for Nucleosynthesis in Stars

The chemical composition of peculiar stars provides clues to the nuclear processes in stellar interiors.

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In 1952 Merrill (*1*) reported that several absorption lines in the spectrum of R Andromeda (R And) and other cool stars were due to the unstable element technetium. Since the longest-lived isotope of technetium has a half-life of 2.6×10^6 years and the age of the oldest stars was thought to be 1000 times greater, it was clear that the technetium in R And had been produced within the recent past. This discovery initiated the field now called observational nuclear astrophysics, in which astronomers deduce the chemical composition of stars and relate the composition to nuclear processes in the stellar environment. In fact, the observation of the surface composition of stars is one of the few methods whereby the theory of stellar structure may be verified.

Why Observe Stars?

Our knowledge of the physical processes in stellar interiors has been built by the assembly of contributions from theoretical astrophysics, nuclear physics, and the observation of stellar surfaces. Direct observation of stellar interiors is precluded by the high opacity of stellar material to photons of all wavelengths and the short mean-free path of particles. The only exception is the neutrino, which can travel from the center of the sun or a star to detectors on the earth (*2*).

By its inaccessibility to direct observation, nuclear astrophysics is typical of much of astronomy in which we combine indirect observation and theory. We can no more send a chemistry set to the interior of Sirius than we can insert a thermometer in a sunspot.

The theoretical astrophysicist can apply the laws of thermodynamics, radiative transfer, and others to large masses of gaseous material and can compute numerical models of stars that specify the run of temperature, density, pressure, luminosity, and so forth, with radius. As nuclear reactions produce the energy that is radiated from the stellar surface, they also cause the chemical composition in the central regions to change, which results in profound changes in the structure of the star. In order to calculate stellar models and predict the chemical changes in stellar interiors, the rates of the various nuclear reactions must be known. Many of the reactions have been studied in the laboratory, but theory must also be employed to extrapolate reaction rates from the laboratory range of energy to the lower energies that are important in stellar interiors. At least one reaction, the simple proton-proton capture followed by a β-decay to produce deuterium, cannot be studied in the laboratory and its rate must be predicted by by the theory of nuclear physics. Stellar evolution and rates of nuclear reactions that are of interest to astrophysicists have recently been reviewed by several authors (*3*).

Considering the great expansion of our knowledge of theoretical astrophysics and nuclear physics, we may ask why it is necessary to observe stars at all, why we cannot predict successfully every step of stellar evolution. The astronomer Sir Arthur Eddington once said that even if man lived on a completely cloudy planet he would know that stars exist simply by investigating the physical laws governing the properties of large spherical masses of gas. Despite Eddington's optimism regarding the power of theory, there are a number of aspects of stellar evolution that are so complex that they are dealt with, even today (30 years later), only approximately and with great difficulty. These processes are just the ones that lead to the loss of mass from stars and the mixing of surface material with deeper layers. Thus the very processes that bring the products of the nuclear reactions in the interior to the surface, where they may be observed, are the ones that cannot be computed in detail.

Positive evidence that stars of large radius are losing mass has been presented by Deutsch (*4*). The rate of mass-loss cannot be established from the observations and the cause of this loss is obscure. Probably the mechanism responsible for gradual loss of mass from red giants is associated with heating of the stellar atmosphere and corona by dissipation of mechanical energy originating in the photosphere. The outer part of the stellar corona then evaporates by a process similar to evaporation of the solar corona, which produces solar wind.

Mixing within stars may be initiated by at least two processes. If the temperature gradient becomes too steep, radiation will not carry all the energy, convection will set in, and the entire convective region will be homogenized. At present the theory of convection cannot predict the depth of mixing or the convective velocities in detail. An-

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Table 1. Comparison of the composition of HD 122563 with that of the sun. Entries are logarithms of the number of atoms of a given species with log N_H arbitrarily set at 12.0. Uncertainties are about 0.3 in the log.

Element	Sun	HD 122563
H	12.0	12.0
Na	6.3	4.3
Mg	7.4	4.9
Al	6.2	4.0
Ca	6.15	3.7
Sc	2.8	0.2
Ti	4.7	2.2
V	3.7	0.7
Cr	5.4	2.8
Mn	4.9	1.9
Fe	6.6	4.1
Co	4.6	1.8
Ni	5.9	2.55
Zn	4.4	2.0
Sr	2.6	−0.1
Y	2.25	− .15
Zr	2.2	− .6
Ba	2.1	−1.4
Ce	1.4	−2.2
Eu	0.8	−2.3

other cause of mixing is the rapid release of energy when a nuclear reaction starts in degenerate material. These "flashes" result in thermal runaways and the development of unstable temperature gradients. They also are very difficult to follow in detail with a computer because hydrodynamic calculations must replace the usual assumption of hydrostatic equilibrium. However, it is sometimes possible for the observational astronomer to infer some of the mixing processes by investigating the chemical composition of stellar surfaces and correlating peculiarities in the composition with the products of nuclear reactions.

Nuclear Reactions of Interest to Astronomers

In the sun and in main-sequence stars of mass smaller than the sun the conversion of hydrogen to helium proceeds by way of the proton-proton chain. After the production of deuterium by

$$H^1(p, \beta^+\nu)\ H^2$$

(p is proton; β^+, positron; and ν, neutrino) another proton capture leads to He^3, and the production of He^4 is completed by one of the following three routes (α is He^4 nucleus; γ, gamma ray; and β^-, electron).

$$He^3(He^3, 2p)\ He^4$$

$$He^3(\alpha, \gamma)Be^7 \rightarrow$$

$$Be^7(p, \gamma)B^8(\beta^+\nu)Be^8(\alpha)He^4$$

or

$$Be^7(\beta^-, \nu)Li^7(p, \alpha)\ He^4$$

The proton-proton chain may be confirmed by the detection of solar neutrinos, since it is the high-energy neutrinos from the decay of B^8 that are detectable by the Davis experiment (*2*). Indirect evidence that Be^7 may be produced and transferred to the surface of carbon stars before decaying to Li^7 (and hence destroyed by proton capture) is provided by the observation of a high content of lithium in carbon stars (*5*).

The conversion of hydrogen to helium through the carbon cycle was the first successfully suggested source of stellar energy (*6*). It is now known that oxygen joins the cycle at temperatures greater than about 25 × 10^6 °K, making it a bi-cycle. The reactions are as follows:

$$C^{12}(p,\gamma)N^{13}(\beta^+\nu)C^{13}$$
$$C^{13}(p,\gamma)N^{14}$$
$$N^{14}(p,\gamma)O^{15}(\beta^+\nu)N^{15}$$
$$N^{15}(p,\alpha)C^{12}$$
$$N^{15}(p,\gamma)O^{16}\ \text{(once in 2500 times)}$$
$$O^{16}(p,\gamma)F^{17}(\beta^+\nu)O^{17}$$
$$O^{17}(p,\alpha)N^{14}$$

All of these can be studied in the laboratory and the rates are quite well established. I will discuss the very considerable evidence confirming the importance of these reactions in modifying the chemical composition of stars in later sections. Nevertheless, let me point immediately to the high content of C^{13} on carbon stars (*7*). The ratio of C^{12} to C^{13}, about 3 or 4 as compared with 90 on earth, is almost exactly the inverse ratio of the cross sections for the first two reactions, confirming beautifully that under equilibrium conditions the C^{12} to C^{13} ratio is established by carbon cycling, and the material so processed is now on the stellar surface.

Following the production of helium a star produces energy in its core by the combination of three helium nuclei to produce carbon and the further capture of a helium nucleus to produce oxygen. Temperatures near 10^8 °K are necessary for these reactions. Near 10^9 °K carbon and oxygen burning can produce a variety of isotopes from neon to sulfur, and under conditions of even higher temperatures a rapid buildup to the elements around iron ensues. Under the extreme temperatures (3 to 5 × 10^9 °K) at which iron is formed, so many reactions take place that the material is nearly in thermal equilibrium, and the relative abundances can be computed approximately without knowing the rates of each reaction.

Beyond iron the coulomb barrier is so large that reactions with charged particles are virtually prohibited and the buildup of heavier nuclei proceeds through neutron capture (*8*). If the time interval between successive neutron captures is very long compared to the β-decay time of the neutron-rich isotopes the sequence is called the slow or "s-process." On the other hand, if a flood of neutrons is released they can be captured very rapidly, building extremely neutron-rich isotopes which later decay to the stability line. This is the rapid or "r-process." The source of neutrons (n) is an interesting problem (*9*). Reactions such as C^{13} (α,n) O^{16} and Ne^{21} (α,n) Mg^{24} are the most likely source of neutrons on a slow time scale, since they can proceed at temperatures near 10^8 °K. A high abundance of C^{13} or Ne^{21} must be present initially, or simultaneous production of C^{13} and Ne^{21} during hydrogen burning and helium burning must occur. The flood of neutrons producing the r-process may occur during supernova explosions or other types of violent events, possibly in quasars. In any event, stars with a great excess of those elements produced by slow neutron capture are well known and will be discussed in detail in the next section. Stars with great excesses of nuclei produced by the r-process have not been definitely detected, but some of the magnetic stars may be candidates.

Table 2. Comparisons of young and old stars with theory of the e-process; T_9 is the temperature in billions of degrees; R, the ratio of total neutrons to protons. Entries are abundances of each element normalized to unity for iron.

Element	Sun	$T_9 = 4$ Log $\rho = 8$ $R = 0.875$	HD 122563	$T_9 = 3$ Log $\rho = 8$ $R = 0.85$	$T_9 = 2$ Log $\rho = 8$ $R = 0.85$
V	0.0013	0.0016	0.0004	0.0006	0.0001
Cr	.063	.13	.05	.125	.026
Mn	.018	.13	.006	.017	.00098
Fe	1.000	1.000	1.000	1.000	1.000
Co	0.012	0.016	0.006	0.009	0.007
Ni	.18	.145	.25	.157	.186

Stellar Observations

There are several types of stars whose chemical composition shows strong evidence that the nuclear processes discussed above actually take place in astrophysical environments and are not just convenient but unprovable hypotheses. The most interesting stars may be divided into three rough groups: (i) extremely old, metal-poor stars; (ii) heavy-element and carbon stars; and (iii) hydrogen-poor stars. Some stars belong to two groups; there are metal-poor stars with an excess of carbon and heavy elements as well as hydrogen-poor stars that are carbon-rich. In the following discussion I will describe examples of each group that have been analyzed for chemical composition and see how each peculiar composition may be interpreted in terms of nuclear astrophysics. Before I discuss peculiar stars it might be well to define normalcy. A substantial number of stars within a wide range of temperatures and luminosity have been found to have the same composition as the sun. Some elements cannot be analyzed in the sun spectroscopically, but the most important of these, helium and neon, have been found in solar cosmic rays and their abundances have been measured by direct counting of particles.

Metal-Poor Stars

If we accept the hypothesis that most of the heavy elements in the normal stars were produced in the interiors of older generations of stars, then most metal-poor objects must have been formed long ago, before production of most of the heavy elements had taken place. The most metal-deficient star yet found is HD 122563, which has been analyzed by several authors (*10*). A photograph of its spectrum is shown in Fig. 1, along with another metal-poor star HD 165195 and the normal star θ Lyra. All three stars have similar temperatures. The results of the abundance analysis of HD 122563 are shown in Table 1. Entries are normalized by letting $\log N = 12$ for hydrogen. In addition to the low abundance of all elements except hydrogen two features are particularly noteworthy. (i) Among the elements near iron (iron-peak elements), nuclei with odd numbers of protons (vanadium, manganese, and cobalt) are more deficient than the elements with an even number of protons (chromium, iron, and nickel). (ii) The heaviest elements, starting with barium, show a substantial additional deficiency with respect to everything else.

Both the physics and the astrophysical environment responsible for the formation of the iron-peak elements are uncertain (*11*). While the temperatures and density must be high (3 to 5×10^9 °K and 10^4 to 10^9 grams per cubic centimeter, respectively) the material does not have time to go to pure statistical equilibrium because some of the β-decays are too slow. The only available calculations (*12*) that predict specific abundance ratios are based upon an assumption of equilibrium (e-process), largely because of the complexity of nonequilibrium calculations. Since they predict the wrong ratio of Ni^{58} to Ni^{60} in the solar system and since their theory cannot be modified to predict the correct ratios of both Ni^{58} to Ni^{60} and Fe^{54} to Fe^{56}, any comparison with observations is necessarily of a very preliminary nature. Nevertheless, this type of comparison is given in Table 2. The entries are normalized by setting the total iron abundance at unity. Individual isotopes are not shown in Table 2 because, for these elements, isotopes cannot be differentiated in stars; thus we must beware of excessive optimism if we find a fit between theory and observation. Except for the manganese abundance a fairly good fit for the total abundances in the sun is obtained for a temperature of 4×10^9 °K, a density (ρ) of 10^8 grams per cubic centimeter, and a ratio of total protons to neutrons (R in Table 2) of 0.875. For the very old star HD 122563 the fit is better for $\rho = 10^8$ grams per cubic centimeter, $R = 0.85$, and a temperature between 2 and 3×10^9 °K. From earlier data Clifford and Taylor derived a temperature near 2.7×10^9 °K (*12*).

It is not surprising that a better fit may be obtained for the very old star HD 122563 than for the sun because the fewer the metals, the fewer supernovae, massive objects, or "what have you" contributed to their composition. For a metal-rich star like the sun it is likely that many types of objects in unknown proportions contributed to the composition of the interstellar medium before the sun was born.

The deficiency of the very heavy elements provides a further clue to the nuclear processes that antedated HD 122563. Apparently the process of neutron capture built elements up to the strontium, yttrium, and zirconium region, but only to a reduced extent in the barium–rare earth region. This could occur if the number of neutrons per initial seed nucleus were only about 30 rather than 80, as needed to build into the barium region. Another possibility is a shortage of iron, which would make it necessary for the neutrons to be captured by lighter elements such as magnesium, silicon, and sulfur, and thus requiring even more neutrons per seed nucleus. It seems likely that all of this occurred in previous stars and that their heavy elements were injected into the interstellar medium and subsequently

Table 3. The logarithmic abundance ratios of various elements to iron (N_e/N_{Fe}) in barium stars as compared to normal stars. The entries are $\log N_e/N_{Fe} - \log N_e/N_{Fe}$ (normal).

Element	HD 116713	HD 83548
Fe	0	0
Co	+0.1	0.0
Ni	+ .1	0.0
Zn	+ .1	0.0
Ge	− .2	0.0
Sr	+ .5	+0.2
Y	+ .7	+ .6
Zr	+ .6	+ .3
Mo	+ .5	+ .4
Ru	+ .6	+ .5
Ba	+1.2	+ .5
La	+0.8	+ .4
Ce	+ .8	+ .4
Pr	+1.1	+ .4
Nd	+0.6	+ .3
Sm	+ .6	+ .4
Eu	+ .3	+ .3
Gd	+ .4	+ .4
Yb	+ .3	0.0
W	+ .9	+0.5

Table 4. The logarithmic abundance ratios of various elements in two CH stars as compared to normal stars. The entries are $\log N_e/N_H - \log N_e/N_H$ (ε Virginis).

Element	HD 26	HD 201626
C	0.0	−0.3
O	<−1.0	<−1.3
Na	−1.4	−1.9
Mg	−0.8	−1.5
Si	− .6	−1.1
Ca	− .7	−1.2
Sc	− .7	−1.5
Ti	− .6	−1.1
Cr	− .6	−1.8
Mn	−1.3	−1.5
Fe	−0.7	−1.5
Ni	− .7	−1.4
Cu	−1.3	
Zn	−0.4	
Y	− .4	−1.2
Zr	− .1	
Ba	+ .6	−0.4
La	+ .5	− .2
Ce	+ .5	− .4
Nd	+ .4	.0
Eu	0.0	<−1.2

Table 5. Nuclear processing in CH stars. The entries are log N with log N_H set arbitrarily at 12.0. In stages III, IV, and V, the O^{18} may be reduced by the reaction O^{18} (α, γ) Ne^{22}.

Isotope	Stage I	II	III	IV	V	VI
H^1	12.0				12.0	12.0
He^4	11.2	11.4	11.4	11.4	11.2	?
C^{12}	7.1	6.3	9.4	9.4	7.6	8.3
C^{13}	5.1	5.7			5.1	<6.6
N^{14}	6.5	7.7			6.5	?
O^{16}	7.5	5.3	5.8	7.0	7.5	<7.7
O^{18}	4.5	4.5	7.7	7.7	6.2	?
Fe	5.1	5.1	5.1		5.1	5.1
Ba	0.6	0.6	0.6	3.6	2.1	1.7

Table 6. Nuclear evolution of a hypothetical star to derive the present abundances of RU Cam. The initial and observed abundance of hydrogen is arbitrarily set at log N_H = 12.0.

Isotope	Stage I	II	III	IV	V	Observed
H	12.0				11.7	12.0
He^4	11.0	11.5	11.4	11.4	11.3	
C^{12}	8.6	7.8	10.5	9.1	9.0	9.0
C^{13}	6.6	7.2		8.5	8.2	8.0–8.3
N^{14}	8.0	9.2		10.5	10.2	
O^{16}	9.0	6.8	7.3	8.1	8.8	<9.0
O^{18}	6.0	6.0	9.2(?)	?	5.7	
Fe^{56}	6.6	6.6	6.6(?)	6.6	6.3–6.6	6.6

incorporated in HD 122563 when it was formed. Almost nothing is known about such stars. They may have been too massive ever to have been stable, and therefore collapsed, thus raising their central regions to high temperatures and densities, followed very rapidly by an explosion (or "bounce").

Heavy-Element Stars

Let us turn our attention to stars whose surface composition appears to have been altered by nuclear processes within the star itself. It would be most interesting if one of the technetium stars had been analyzed in detail, but they are all so cool and their spectra are so complex that no analysis of a technetium star has yet been attempted. However, nine stars which show similar anomalies, that is, excessive abundances of various elements from strontium to samarium, have been analyzed (*13*). The difference in composition between two of them and normal stars is shown in Table 3. With the iron abundance as a standard, the ratios of various heavy elements are compared to iron and the logarithm of the ratio is given.

The elements immediately heavier than iron (cobalt through zinc) are about normal. Starting with the next row of the periodic table, there are moderate excesses (factors 2 to 5) in both stars. The most spectacular excesses appear in the sixth row of the period table from barium through samarium, but only for HD 116713. For HD 83548 the excesses of the very heavy elements are no greater than for the group from strontium to ruthenium. Starting with europium the enhancement is less evident, almost certainly because these elements are produced less readily by slow neutron capture and more probably by rapid neutron capture, which is not likely to have occurred in a stable star.

Since reliable abundances for the light elements carbon, nitrogen, and oxygen are not available for these stars, the composition changes in the stellar interior cannot be followed in detail. However, a discussion of the abundance ratios in terms of the flux of neutrons that were absorbed by the iron-peak elements has been presented by Danziger (*13*). He interprets the larger discontinuity in HD 116713 in terms of a larger neutron flux which would process a higher percentage of the material into very heavy elements. For HD 83548, on the other hand, a more modest neutron flux processed less material into the region from barium to samarium.

Carbon Stars

The coolest stars may be divided into those that show oxides such as TiO, VO, and ZrO in their spectra and those that show carbon compounds such as CH, CN, and C_2. The latter type are called carbon stars. The sharp dichotomy seems to result from the balance of molecular equilibriums involving the tightly bound molecule CO. Calculations indicate that in cool stars the formation of CO is complete, so that whichever element is less abundant is entirely tied up. If oxygen is more abundant than

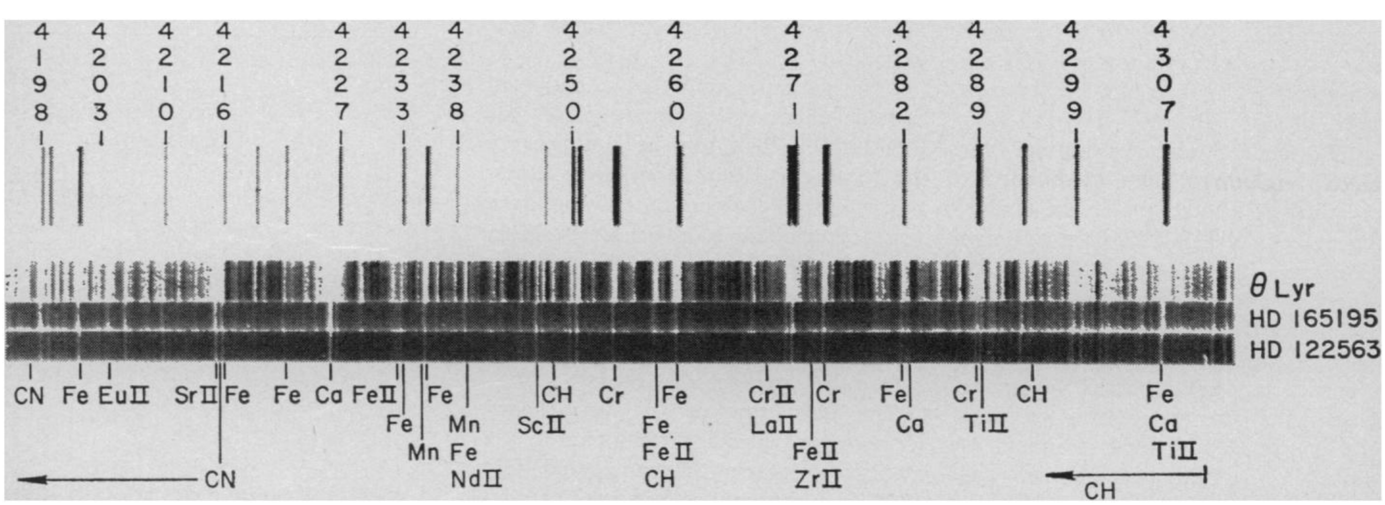

Fig. 1. Negative print of two metal-poor stars and the normal star θ Lyra. Absorption lines are light and are identified below; their weakness is evident in the two metal-poor stars. A laboratory emission spectrum of iron is shown above. [From *Astrophys. J.* **137**, 295 (1963)]

carbon, oxides, but no carbon compounds, will be found; if carbon is more plentiful than oxygen, a carbon star will be observed.

The cool carbon stars show spectra that are well known for their complexity and inscrutability. The atomic lines and molecular bands are so crowded that nowhere in the spectrum is the true continuum seen. Furthermore, the abundance of hydrogen in some of the carbon stars may be so low that other elements provide the main source of continuous opacity. In that case the basic structure of the stellar atmosphere cannot be calculated a priori. However, a number of carbon stars are hotter than 4000°K; their spectra are simpler, and the sources of opacity are usually known.

The CH Stars

An interesting subclass of carbon stars is a group with weak metallic absorption lines and very strong features of the molecule CH. These CH stars show extremely high space velocities, which indicate stellar orbits that carry them far into the halo of our galaxy.

As with other halo stars, the two CH stars that have been studied in detail were found to be metal-poor (*14*). The weak lines and clearly defined continuum allow an accurate analysis of the chemical composition. Their abundances, as compared to the standard star ε Virginis, are shown in Table 4. Of particular interest, in addition to the high carbon abundance and low metal content, is the substantial excess (relative to iron) of barium and the rare earths. These elements are precisely the ones that are enhanced in the heavy-element stars described above and are built to a high abundance during a slow process of neutron capture—the s-process. Again the r-process element, europium, shows less enhancement than the lighter rare earths. Another point of interest is the low content of C^{13} in these stars. In HD 201626 less than 2 percent of the carbon is C^{13}, and in HD 26 less than 10 percent.

A scheme for successive nuclear reactions, mixing, and homogenization was proposed (*14*) to account for the composition of the CH stars; it is outlined in Table 5. In stage I the hypothesized initial composition is given. The relative abundances are taken from the solar system, except that all elements heavier than helium are reduced by a factor of 30, the observed metal deficiency in HD 201626. The effects of transforming all the hydrogen into helium and allowing the CNO nuclei to come into equilibrium by the carbon cycle at 6×10^7 °K are shown in stage II. The result of letting 3 percent of the helium burn to carbon and the scouring out of C^{13} and N^{14} by reactions with helium are given simultaneously in stage III. Next we must invoke mixing because the amount of C^{13} that releases neutrons between stages II and III is insufficient by a factor of 10 to 20 to provide 50 to 100 neutrons per initial iron nucleus to build the observed excess of barium and rare earths. By mixing less than one proton per nucleus of C^{12}, virtually all the protons are captured by C^{12}, forming C^{13} which reacts almost immediately with the helium to produce the necessary neutrons. The processing of only 1/250th of the C^{12} nuclei produces all the necessary neutrons, does not deplete the C^{12}, or build too much O^{16}, as shown in stage IV. Three percent of the iron has gone to barium while the rest has been converted to other elements in the barium–rare earth group. The abundances in stage IV show a much greater excess of carbon and heavy elements than is observed, but a continuation of mixing at such a low temperature that no further reactions beyond helium occur will dilute the great excesses in stage IV. Three percent of the material of stage IV and 97 percent of unaltered material of stage I yield the abundances of stage V, which are very close to the observations shown in stage VI. The predicted carbon abundance is a little low; it could be raised to the observed value by including 5 percent of stage III material which has a high abundance of C^{12} and little else of importance.

Table 7. Composition of the R Corona Borealis stars. Entries are logarithms of the number of atoms, with log N_H set arbitrarily at 12.0 for the normal star.

Element	Normal star	RCrB	RY Sgr
H	12.0	8.6	8.3
He	11.2	11.6	11.6
C^{12}	8.6	9.6	9.7
C^{13}	6.6		< 8.0
N	8.0		7.6
O	9.0		8.0
Fe	6.6	6.2	6.2
Ba group	2.1	1.7	1.5

Table 8. Composition of HD 30353. Entries are logarithms of the number of atoms, with log N_H set at 12.0 for normalcy.

Element	Normal	HD 30353
H	12.0	7.6
He	11.2	11.6
C	8.7	6.2
N	8.0	9.2
O	9.0	7.5
Ne	8.5	8.5
Si	7.5	7.6
S	7.3	7.8

RU Cam, a Former Variable Carbon Star

The composition of RU Camelopardalis is rather different from that of the CH stars. It was formerly a variable star with a period of 22 days but ceased its variations in 1964. I obtained spectra in 1965 in order to study the variation, only to find out a few months later that the variations had ceased. Thus the spectra were more suitable for chemical analysis than they might have been had the star continued to pulsate. Results of the chemical analysis are shown in the last column of Table 6, which will be used to describe a likely course of evolution leading to that composition (*15*). Because the star is faint and was observed only in the visual and red regions of the spectrum, abundances of many elements in RU Cam could not be obtained. Even such limits as the fact that carbon is more abundant than oxygen and less abundant than log $N = 9.0$ on a scale of log $N_{\text{hydrogen}} = 12.0$ can be used to set limits on the nucleosynthesis outlined in the first five columns. Again we start with the solar composition in stage I (Table 6). Stage II shows the effect of converting the hydrogen to helium and rearranging the CNO nuclei in accordance with the carbon cycle. In stage III one-third of the helium is converted into carbon and at the same time the C^{13} and N^{14} are burned out, as discussed for the CH stars. In stage IV the material from stage III is mixed with protons that burn by the carbon cycle, presumably by passing through a region of shell burning. This reprocessing is essential in order to raise the C^{13} content. The temperature in the shell is limited to values below 8×10^7 °K to prevent C^{13} from being destroyed and Na^{23} from being synthesized by Ne^{22} (p, γ) Na^{23}. A likely temperature is around 6×10^7 °K at which any remaining O^{18} reenters the carbon cycle through O^{18} (p, α) N^{15}. Stage V consists of a

Table 9. Abundance ratios in HD 30353 and a possible sequence of events to explain them; T_6 is temperature in millions of degrees Kelvin.

Element ratio	Normal	HD 30353	$T_6 = 10$	$T_6 = 25$	$T_6 = 25 \rightarrow 10$
C : O	0.5	0.05	Not in equilibrium	0.7	0.12
N : O	.1	50.0	Not in equilibrium	60.0	60.0
C : N	5.0	0.001	0.002	0.012	0.002

mixture of one-half of stage IV material and one-half of the original material of stage I. The observations are given in the last column. The derived abundances fit the observations within the uncertainties (about 0.3 in the log) of the data and predict that nitrogen should be in large supply. This prediction cannot be confirmed from the spectrograms now available, but higher dispersion spectra should be analyzed in the future.

Hydrogen-Poor Carbon Stars

The hottest carbon stars are a group of variables called the R Corona Borealis stars after the prototype of the class. Their light shows sudden irregular decreases that do not really concern us here. Two stars, RCrB and RY Sgr, have been analyzed for chemical composition while at their normal level of brightness (*16*). Their compositions are shown in Table 7. Once again we ask how material of this composition could appear on the surface of a star. Aside from the ad hoc hypothesis that these stars originally formed from material shown in Table 7, it is impossible to explain the abundance except in terms of nuclear burning and mixing. Unfortunately, the intermediate abundance of nitrogen and oxygen prevent the data from severely limiting the nuclear processes that may have occurred. If nitrogen were in high abundance, only CNO cycling could produce the observations. If nitrogen were absent, there would be complete scouring out of N^{14} by $N^{14}(\alpha, \gamma)F^{18}(\beta, \nu)O^{18}$. Similar arguments are applicable to the oxygen abundance. For RCrB and RY Sgr, one can only generalize as follows: Over 99 percent of the original surface hydrogen has been either processed to helium or removed. Some helium has been converted to C^{12}. No substantial amount of the new C^{12} has been converted to C^{13}, otherwise there would be either a high content of C^{13} or a high abundance of heavy elements built up by neutron captures as $C^{13}(\alpha, n)O^{16}$ depleted the C^{13}.

A large group of cooler hydrogen-deficient carbon stars have recently been analyzed by Warner (*17*). The abundances appear to be similar to those of the RCrB stars and none of them show any C^{13}. Warner has analyzed the abundance changes along similar lines to those described above for the RCrB stars. A further group of hydrogen-deficient stars has high temperatures, that is, 15,000° to 30,000°K, and high carbon abundances. Some of them show a high nitrogen abundance and may be similar to the most revealing of all peculiar stars, the nitrogen-rich group.

Nitrogen Stars

While the RCrB stars show a deficiency of hydrogen and an excess of carbon, another group of peculiar stars is also deficient in hydrogen but has a high abundance of nitrogen rather than carbon (*18*). Two such stars are known, the fourth-magnitude star υ Sgr and HD 30353.

A year ago two graduate students and I completed a preliminary chemical analysis of the atmosphere of HD 30353 (*19*). The analysis was one of the most fascinating with which I have been involved because we got into a vicious circle of not being able to establish the abundance without knowing the effective temperature, not knowing how to interpret the star's continuous energy distribution in terms of the temperature without knowing the source of opacity, and finally not being able to compute the opacity without knowing the chemical composition. The vicious circle was broken with the help of model atmospheres of hydrogen-poor stars by E. Böhm-Vitense (*20*) and some judicious first-order approximations that could be improved as we traveled about the circle. Our best value of the temperature was 10,000°K; the mean electron pressure appears to be 2 dynes per square centimeter; and the opacity is due to free-free transitions of the negative helium ion, photoionization of neutral nitrogen, and electron scattering.

The chemical composition (normalized to maintain the same number of nucleons per gram of material) of the light elements is given in Table 8. Helium and nitrogen are greatly enhanced while hydrogen, carbon, and oxygen are grossly depleted. This is exactly what might be expected in material that has been through the carbon cycle, and the abundances of carbon, nitrogen, and oxygen may be compared with the calculations of Caughlan and Fowler (*21*).

When this comparison is made, the ratio of nitrogen to oxygen is seen to be characteristic of hydrogen burning by the carbon cycle at 24×10^6 °K, while the ratio of nitrogen to carbon is characteristic of 10×10^6 °K. This difference is puzzling until we note that the only way HD 30353 has been able to show the material that was once in its interior is by having lost a substantial fraction of its mass. Since the central temperature of a main-sequence star depends about linearly on its mass, its central temperature may well have decreased with time. In Table 9 a scheme of evolution is given which yields the observed abundances. The first two columns show the observed

Table 10. Summary of abundances in peculiar stars of various types. Entries are log N normalized to log $N_H = 12.0$ for stars of normal hydrogen content and to log $N_{He} = 11.6$ (to yield the same total mass) for hydrogen-poor stars.

Element	Normal star	Metal-poor stars	Barium stars	CH stars	RU Cam	RCrB stars	HD 30353
H	12.0	12.0	12.0	12.0	12.0	8.5	7.6
He	11.2					11.6	11.6
C^{12}	8.6			8.3	9.0	9.6	6.2
C^{13}	6.6			< 6.6	8.0–8.3	< 8.0	
N	8.0					7.6	9.2
O	9.0			< 7.7	< 9.0	8.0	7.5
Fe	6.6	4.1	6.6	5.1–5.9	6.6	6.2	
Sr	2.6	−0.1	3.2	1.4–2.3	2.6(?)	2.2	
Ba	2.1	−1.4	3.1	1.7–2.6	2.1(?)	1.6	

abundance ratios in normal stars and in HD 30353, respectively. In the third column the ratio of carbon to nitrogen is given at $T = 10 \times 10^6$ °K; the other ratios do not come into equilibrium at 10×10^6 °K because the reaction O^{16} (p, γ) F^{17} proceeds too slowly at such low temperatures. The fourth column shows the ratios achieved at $T = 25 \times 10^6$ °K. The ratio of nitrogen to oxygen, as established at that temperature, is not affected as the temperature is reduced to 10×10^6 °K. However, at the latter temperature much of the carbon is transformed into nitrogen and the ratios of both carbon to oxygen and carbon to nitrogen are reduced to values within about a factor of 2 of the observed composition. The uncertainty in the observations is at least a factor of 2, so we can say that the agreement is satisfactory.

General Considerations

This review is summarized in Table 10, which contains the observed abundances in each type of evolved star; similar stars have been grouped together. The differences are very marked, showing the wide range of physical conditions to which stellar material may be subjected and yet somehow reach the stellar surface.

In order to indicate whether "nuclear cooking" is a purely ad hoc process or a realistic description, it is relevant to compare the number of observed facts with the number of hypotheses. It is probably fair to say that each entry in Table 10, except the column for normal stars and the row for hydrogen, should be classed as a fact. Thus 30 facts have been explained.

The specification of hypotheses is more difficult. Suppose we start with the basic assumptions of stellar structure. These involve (i) hydrostatic equilibrium, (ii) mass continuity, (iii) continuity of energy flow, (iv) equation of state, (v) the temperature gradient, and (vi) the radiative opacity. Next we must hypothesize the rates of *all* of the nuclear reactions, including the six reactions of the carbon cycle, the two reactions of pure helium burning, and the important reactions C^{13} (α, n) O^{16} and N^{14} (α, γ) F^{18} ($\beta^+ \nu$) O^{18}. Lastly we must hypothesize mixing or loss of mass, or both, for each star, about two more hypotheses for each star in addition to the 16 hypotheses of nuclear physics and stellar structure. The total number of hypotheses is about 28.

It is certainly comforting that the number of hypotheses is less than the number of facts. Because of the inherent complexity of astrophysical environments and their changes we cannot expect that the number of necessary hypotheses can be reduced. Perhaps we can feel that the views outlined in this article are following the correct line of approach if further peculiar stars can be added to Table 10 and more elements can be analyzed in stars already in the table, without invoking additional hypotheses or requiring very special conditions of mass-loss and mixing.

References

1. P. W. Merrill, *Astrophys. J.* **116**, 21 (1952); *Science* **115**, 484 (1952); J. L. Greenstein, in *Modern Physics for the Engineer*, L. N. Ridenour, Ed. (McGraw-Hill, New York, 1954), p. 235; A. G. W. Cameron, *Astrophys. J.* **121**, 144 (1955).
2. J. N. Bahcall and R. Davis, Jr., in *Stellar Evolution*, R. F. Stein and A. G. W. Cameron, Eds. (Plenum Press, New York, 1966), pp. 241–244.
3. I. Iben, Jr., *Science* **155**, 785 (1967); W. A. Fowler, G. R. Caughlan, B. A. Zimmerman, in *Annual Review of Astronomy and Astrophysics*, L. Goldberg, Ed. (Annual Reviews, Palo Alto, Calif., 1967), vol. 5, pp. 525–570.
4. A. J. Deutsch, *Astrophys. J.* **123**, 210 (1956).
5. A. McKellar, *Publ. Astron. Soc. Pac.* **52**, 407 (1940); S. Torres-Peimbert and G. Wallerstein, *Astrophys. J.* **146**, 724 (1966); A. G. W. Cameron, *ibid.* **121**, 144 (1955).
6. H. Bethe, *Phys. Rev.* **55**, 434 (1939); *Science* **161**, 541 (1968).
7. A. McKellar, in *Stellar Atmospheres*, J. L. Greenstein, Ed. (Univ. of Chicago Press, Chicago, 1960), pp. 569–584.
8. P. A. Seegar, W. A. Fowler, D. D. Clayton, *Astrophys. J. Suppl. Ser.* **11** (No. 97), 121 (1965).
9. H. Reeves, *Astrophys. J.* **146**, 447 (1966).
10. G. Wallerstein, J. L. Greenstein, R. A. R. Parker, H. L. Helfer, L. H. Aller, *ibid.* **137**, 280 (1963); B. E. J. Pagel, *Roy. Observ. Bull.* No. 87 (1964), p. 127; S. C. Wolff and G. Wallerstein, *Astrophys. J.* **150**, 257 (1967).
11. W. A. Fowler and F. Hoyle, *Astrophys. J. Suppl. Ser.* **9** (No. 91), 201 (1964); D. Bodansky, D. D. Clayton, W. A. Fowler, *Phys. Rev. Lett.* **20**, 161 (1968).
12. F. E. Clifford and R. J. Tayler, *Mem. Roy. Astron. Soc.* **69**, 21 (1965).
13. E. M. Burbidge and G. R. Burbidge, *Astrophys. J.* **126**, 357 (1957); B. Warner, *Mon. Notic. Roy. Astron. Soc.* **129**, 263 (1965); I. J. Danziger, *ibid.* **131**, 51 (1965).
14. G. Wallerstein and J. L. Greenstein, *Astrophys. J.* **139**, 1163 (1964); A. Schadee, *ibid.* **151**, 239 (1968).
15. R. Farraggiana and M. Hack, *Z. Astrophys.* **66**, 343 (1967); G. Wallerstein, *Astrophys. J.* **151**, 1011 (1968).
16. L. Searle, *Astrophys. J.* **133**, 531 (1961); I. J. Danziger, *Mon. Notic. Roy. Astron. Soc.* **130**, 199 (1965).
17. B. Warner, *Mon. Notic. Roy. Astron. Soc.* **137**, 119 (1967).
18. W. P. Bidelman, *Astrophys. J.* **117**, 25 (1953).
19. G. Wallerstein, T. F. Greene, L. J. Tomley, *ibid.* **150**, 245 (1967).
20. E. Böhm-Vitense, *ibid.*, p. 483.
21. G. R. Caughlan and W. A. Fowler, *ibid.* **136**, 453 (1962).