The core is extremely hot and lies in a deep potential hole. The outer iron material is evaporated and freezes very quickly, preserving the iron abundance distribution at a high characteristic equilibrium temperature. Evaporation of the iron-neutron transition region produces neutron-rich nuclei by neutron capture on a fast time-scale. In very massive super-novae (type II?) the neutron core is too hot to contain seed nuclei; when some of it evaporates only deuterium and helium can be formed. Less massive super-novae (type I?) may contain seed nuclei in the neutron core and so produce large amounts of heavy elements by neutron capture on a fast time-scale, including the special nucleus ^{254}Cf.

The type II super-nova described above can thus be expected to produce nearly the entire solar system abundance distribution of the elements in the correct relative proportions.

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5. OBSERVATIONS ON ELEMENT ABUNDANCES IN STARS

E. MARGARET BURBIDGE AND G. R. BURBIDGE

The basic astronomical information relating to the synthesis of the elements in stars is the determination of abundances of the elements throughout as large a sample of the universe as possible. The information available may be divided into three main parts.

1. The first consists of abundances in the Sun and solar system, supplemented by other nearby stars. These provide a so-called 'local sample'. Detailed study of them has formed the basis for the theory of the origin of the elements in stars [1] outlined by Professor Fowler in his introductory paper.

2. The second part concerns abundances in stars of different ages and locations in the Galaxy. If hydrogen alone is primeval, the oldest stars in our Galaxy today would be expected to contain the smallest proportion, relative to hydrogen, of elements heavier than hydrogen.

3. The third division of the observational material consists of the determinations of relative abundances in individual peculiar stars, in whose interiors nuclear reactions have been occurring. These provide the most direct observational evidence for the theory. Such stars will show *over-abundances*, relative to the normal or average, of those elements which have been built in their interiors, and an under-abundance of hydrogen if this has been consumed. For such effects to become visible on the surface, mixing between the core and envelope of the star must have occurred, and this only happens at a fairly late stage in a star's evolutionary history.

4. To these three main divisions may be added a fourth, perhaps less intimately connected with stellar evolution, but of great intrinsic interest. This concerns the anomalous abundances determined in magnetic A- and F-type stars by us [2] and by Margharita Hack [3]. According to the work by Fowler and us [4] these are thought to be localized on the stellar surface and to be due to nuclear reactions initiated by magnetically accelerated particles.

To return to the first sub-division, the Sun provides evidence on only about half of the first 83 elements up to bismuth. Relative abundances of the isotopes, which are so much more informative than element abundances alone for constructing a theory, cannot be obtained from the Sun. For isotopic abundances and heavy element data one must turn to terrestrial and meteoritic analyses.

Aller has recently compiled a summary of astronomical results on abundances [5]. Also, a re-determination of the solar abundances has been made by Goldberg, Aller and Müller [6] in which the main changes from earlier work are that the metals from chromium to cobalt are lower in abundance by an average factor of two, while the value for lead is considerably lower. A serious problem for the heavier elements is the lack of knowledge of *f*-values. The suggested change in lead is due to an experimental *f*-value considerably higher than the calculated one used previously, but the value is still very uncertain, and preliminary work by King at California Institute of Technology indicates a lower value than that used by Goldberg, Aller and Müller. The theory of the slow neutron-capture process predicts a higher abundance than that obtained by them.

With current techniques, the abundance of helium can be determined only in hot stars, and it cannot be assumed that the abundance in the Sun is the same as this. The hot stars are in general much younger than the Sun, and have therefore been formed out of material which may have been enriched in helium produced by many subsequent generations of stars. The average abundance of helium in our Galaxy is therefore not known.

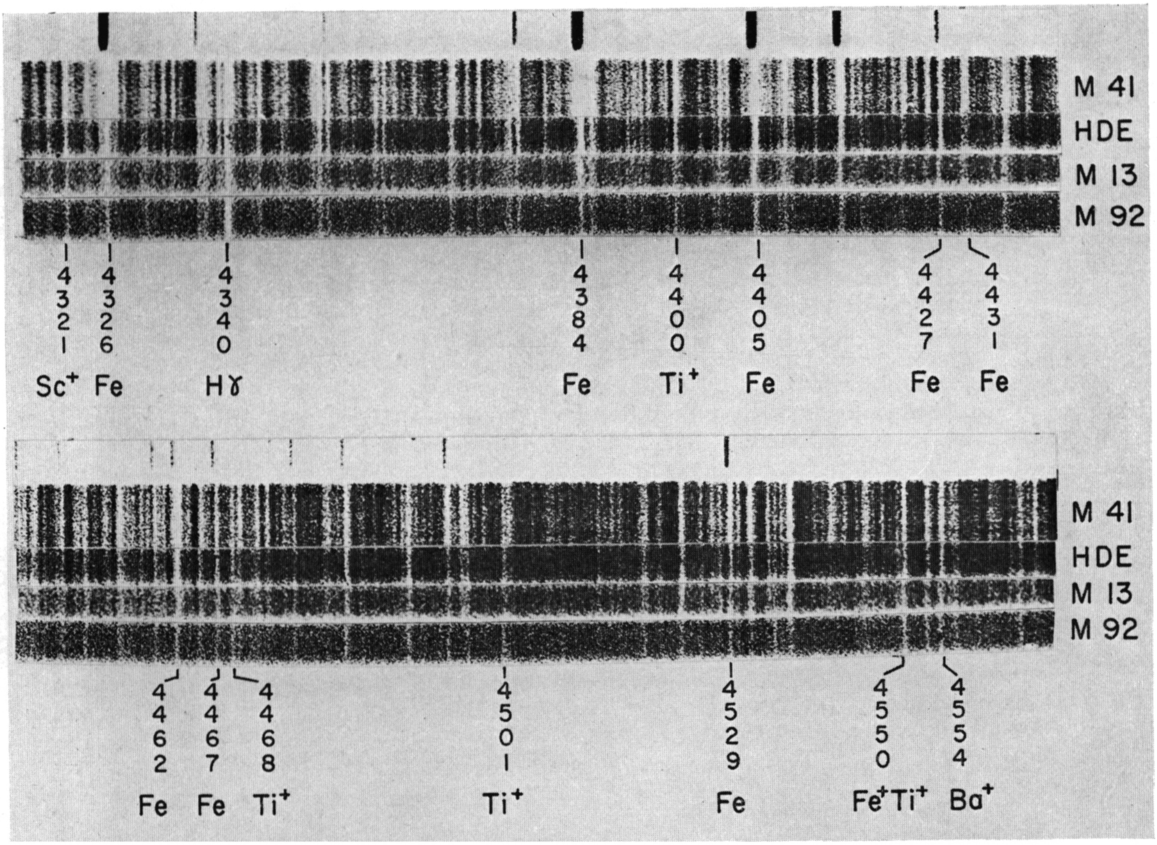
This leads to the second main sub-division, the comparison of abundances of elements heavier than hydrogen in stars of different ages and, if possible, in different galaxies. Since the work of Chamberlain and Aller [7], considerable quantitative as well as qualitative evidence has accumulated for such an 'ageing effect'. Stars in the solar neighbourhood whose velocities show that they belong to the halo or spherical population II have metal abundances that are smaller by factors of 10 or more than the solar value. Some hitherto unpublished and very recent work has kindly been made available for this symposium. At Kiel, Baschek, working on spectra obtained by Unsöld at Mount Wilson of HD 140283, obtained a ratio of metals to hydrogen only one-hundredth of the solar value. Analysis of Greenstein's Palomar spectra of K giants in the globular clusters M 92 and M 13 by Helfer and Wallerstein [8] has given metal abundances only one-hundredth to one-thousandth of the local average, while a K giant in the relatively young galactic cluster M 41, observed as a check, has approximately the same abundances as the Sun. Plate III reproduces the spectra analysed by Helfer and Wallerstein; the fourth spectrum is that of the very high-velocity star HDE 232078.

Stars in the solar neighbourhood which have intermediate population characteristics have intermediate abundances of the metals (low by factors of 2 to 10), according to the published work of many authors [9]. Up to the present, no stars had been shown to have a significantly higher metal content than the Sun, but Santirocco and Savedoff at Rochester have found that the F-type star 20 CVn has a metal content higher by a factor of about 5 than the Sun.

The ageing effect has usually been found to apply approximately equally to elements formed by most of the eight processes discussed by Burbidge, Burbidge, Fowler and Hoyle [1], but Abt at Yerkes has found evidence that some stars far from the galactic plane contain abundances of the *s*-process elements (scandium, zirconium, lanthanum, and cerium) that are low, relative to iron, by factors of 3 to 20.

More study is needed of possible variations between the products of different processes. Good examples would be calcium, titanium, iron, barium, and europium. The compositions of stars in clusters should be studied, since the ages of these can be determined from photometry. Programmes are under way at Yerkes and McDonald and at Mount Wilson and Palomar on this problem. The difficulty concerning helium is the same as in the Sun. Perhaps a return to an earlier method of attack will ultimately be valuable. Calculations such as Hoyle's [10] of main sequences for stars with different helium content and different metal content (which can be determined) may enable us to deduce the helium content of clusters that can be accurately observed both photometrically and spectroscopically. The work of Morgan and Mayall [11] has pointed the way towards the much harder problem of determining abundances in other galaxies, and of studying the possible relation to galactic form.

PLATE III



Portions of the spectra of four K stars of different ages which have very different chemical compositions. The top spectrum is of a star in the relatively young galactic cluster M 41, the next is the very high-velocity star HDE 232078, and the lower two are of stars in the globular clusters M 13 and M 92. Analysis by Helfer, Wallerstein, and Greenstein [8] has shown that the metal content varies from near the solar value in M 41 to factors of one-hundredth to one-thousandth lower in M 92 (courtesy of *Astrophysical Journal*).

In the third sub-division, let us consider individual stars in which the products of nuclear reactions in the interior have reached the surface. Since the time-scales for the equilibrium process, the rapid neutron-capture process, and the *p*-process are all short and these reactions are associated with instability and explosion, we should expect to find only stars that have undergone hydrogen burning, helium burning, the slow neutron-capture process, and possibly the alpha-process. This is indeed the case. Abundance anomalies are found among the variable and non-variable red and yellow giants, in hot sub-dwarfs, in white dwarfs, and also among a few rare high-luminosity stars. In the latter three groups, hydrogen exhaustion can be found together with richness in helium, and in hot sub-dwarfs, a high abundance of nitrogen produced in the CNO-cycle [12]. Well known are the carbon and nitrogen sequences of the Wolf-Rayet stars, where interplay between hydrogen- and helium-burning may be responsible.

The same processes, and the *s*-process in addition, are evidenced by the carbon stars, with their high carbon-to-oxygen ratio and, in many cases, a C^{13}/C^{12} ratio higher than in the solar system. C^{12} is produced by helium-burning, while C^{13} is produced by the CNO-cycle from C^{12} in the ratio of 1 to 4·6. Earlier determinations of the observed ratio in some carbon stars gave 1 to 3, but recent work communicated to us by Wyller at Swarthmore shows that in the star 19 Psc the ratio is lower than this, perhaps of the order of 1 to 10. The star 19 Psc also shows the unstable element technetium, produced by the *s*-process (slow neutron capture).

The S-type stars and the Ba II stars show over-abundances of strontium, yttrium, zirconium, barium, and the rare earths, all produced by the *s*-process. Detailed analysis of the Ba II star HD 46407 [13] shows good agreement with the predictions of the *s*-process theory. The unstable element technetium shows strongly in S stars. The results of the alpha-process may be responsible for the peculiar spectra of some white dwarfs. All these examples have been described in detail elsewhere [1], and are illustrated in Plates 1, 2, and 3 of reference [1].

A final point concerns the element deuterium. The abundance on Earth is about one part in 6000 of hydrogen. The abundance in the interstellar gas is not known, and deuterium has not been detected in stars. However, the work of Fowler and us [4] has suggested that it may be produced in the surfaces of stars with magnetic fields, and the work of Severny [14] and Goldberg, Mohler and Müller [15] has provided evidence for its presence in solar flares.

To sum up, we may conclude that there is a wealth of observational evidence now for the formation of elements from hydrogen in stars.

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6. ON SOME UNSOLVED QUESTIONS IN THE THEORY OF THE ORIGIN OF THE ELEMENTS

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In the preceeding reports an elegant theory of the origin of the elements has been outlined. This theory aims to be a comprehensive one. With the exception of D, Li, Be, B, the origin of all other nuclides is explained by thermonuclear reactions and subsequent neutron capture.

But some difficulties arise in connexion with two groups of nuclides: the iron peak and the by-passed nuclei.

The possible modes of formation of the by-passed nuclei are (γ, n), $(\gamma, 2n)$ ...; $(n, 2n)$, $(n, 3n)$ ...; (p, n), $(p, 2n)$ ..., and (p, γ) reactions.

Of all the processes listed only the (p, γ) process has no energy threshold and may proceed in a sub-barrier thermonuclear fashion. It was hitherto assumed that by-passed nuclei are formed by '*p*-process' consisting of a sequence of such rapid thermal (p, γ) reactions.

In order to penetrate the high barriers involved, the temperature must be of the order of several billion degrees. At such temperatures the reactions become reversible. So the *p*-process turns out to be a sequence of rapid thermal reversible reactions. According to the principle of microscopic reversibility such reactions must inevitably lead to a thermodynamic equilibrium.

We do not mean total equilibrium between all nuclides, but a partial equilibrium between by-passed nuclides and their isobars on the main path. A simple analysis of observed abundances shows the absence of such equilibrium for all by-passed nuclides besides the iron peak.

Let us see which non-equilibrium, slow processes are possible. The capture of a proton is followed by emission of a γ-quantum only if the energy of the compound nucleus is lower than that needed for the emission of a neutron. If the energy exceeds this threshold the (p, n) reaction sets in and radiative capture becomes negligible. The threshold for (p, n) reactions is very high for light nuclei and drops sharply near $A = 50$. At higher mass numbers there is a number of nuclides for which the principal reaction with protons is (p, n) in the energy range near 2 MeV. After the next energy threshold near 10 MeV is surpassed the $(p, 2n)$ reaction sets in. These processes may provide an additional source of neutrons for the main line of nuclear synthesis by slow neutron capture.

Let us consider the following curious process: a (p, n) reaction with subsequent transition back to the initial nucleus by positron emission or electron capture. This leads ultimately to net transition of protons into neutrons. If the neutron width is much larger than the radiation width, the nuclei are not consumed and act as a catalyst. If these nuclei can be formed by slow neutron capture, the process acquires an auto-catalytic character. The nucleus generates neutrons for its own synthesis. If $(p, 2n)$ is important, the formation of heavier nuclei stops and concentration of the nucleus near the low (p, n) threshold grows exponentially. This may be regarded as a plausible non-equilibrium explanation of the iron peak. From the values of (p, n) threshold energies it can be seen that neutron capture should cease at the nuclei ^{55}Mn, ^{57}Fe and ^{59}Co. These should be transformed into their most abundant neighbours ^{54}Fe, ^{56}Fe and ^{58}Ni by subsequent $(p, 2n)$ reactions, followed by β-decay in case of ^{56}Fe.