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NUCLEAR REACTIONS AND ELEMENT SYNTHESIS IN STELLAR ATMOSPHERES*

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ABSTRACT

A modified discussion of surface nuclear reactions in magnetic stars is given. The anomalous abundance effects found in magnetic stars are briefly described. It is suggested that the processes of particle acceleration are similar to those taking place in the solar atmosphere which give rise to the cosmic ray bursts observed by Wild, Roberts, and Murray, and to the solar component of cosmic radiation. Calculations of the rate of loss of energy following particle acceleration suggests that the duration of the hot spot is $1 \lesssim$ sec. It is estimated that in the region of acceleration (p, n) reactions will enable a ratio $n_n/n_p \simeq 10^{-2}$–10^{-3} to be built up. The majority of these neutrons will diffuse from the excited regions and form deuterium in the quiescent atmosphere. This deuterium will be continuously built up and re-acceleration will lead to the release of neutrons, some of which will be captured by the Fe group, eventually giving rise to the observed anomalous abundances of the heavy elements. Also the reaction $H(d, \gamma)\,He^3$ may give rise to the formation of some He^3.

I. OBSERVATIONAL REASONS FOR CONSIDERING SURFACE NUCLEAR REACTIONS

As a class, the 'peculiar' A and F stars have long been known to show apparent anomalies in the spectrum lines of certain elements. It is also certain from the work of H. W. Babcock that there is a very good correlation between spectral peculiarities and the existence of a strong magnetic field. In fact, as far as known there is a one-to-one correlation between spectral peculiarities of this sort and the existence of a magnetic field. For a long time it was not known whether or not the spectral peculiarities were indications of real abundance anomalies in the stellar atmospheres, as they might have been the result of unusual ionization and excitation conditions. However, recent curve-of-growth analyses have shown that the

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abundance anomalies are real. The results for three 'peculiar A' stars, α^2 Canum Venaticorum (Burbidge and Burbidge [1]), HD 133029 (Burbidge and Burbidge [2]), and HD 151199 (Burbidge and Burbidge [3]) are shown in Table 1. The abundances were determined relative either to a standard star of about the same spectral type, or to the sun. Of these stars, the first is a well-known spectrum and magnetic variable, and the abundances which are given in the table are mean values, obtained through the period of variation. In some cases the variations in equivalent width of spectrum lines through the period are considerable, and lead to variations in the derived abundances by factors of 5 or, in the case of europium, even more. These represent changes which may be due to separation of elements in localized areas on the stellar surface (Deutsch [4]), perhaps connected with hydromagnetic phenomena through the magnetic variation, and we shall be concerned only with the enhancement of certain element abundances in the stellar atmosphere as a whole, so that these variations are outside the scope of our work. The second star in Table 1 is a magnetic variable, but apparently not a spectrum variable. The third star probably has a magnetic field, according to recent work by Babcock.

Table 1. *Abundances of the elements in three 'peculiar A' stars, relative to those in a normal star*

Element	α^2 CVn	HD 133029	HD 151199
Mg	0·4	1·4	1·2
Al	1·1	2·2	—
Si	10	25	1·3
Ca	0·02	0·05	2·6
Sc	0·7	—	—
Ti	2·6	2·3	—
V	1·3	3·2	—
Cr	5·2	10·3	1·8
Mn	16	15:	9
Fe	2·9	4·1	1·1
Ni	3·0	2	—
Sr	14	11·5	65
Y	20:	—	—
Zr	30	40	—
Ba	0·9	—	0·6
La	1020:	200:	—
Ce	400	190	—
Pr	1070	630	—
Nd	250	200	—
Sm	410	260	—
Eu	1910	640	130
Gd	810	340	—
Dy	760	460	—
Yb	—	—	—
Pb	1500	1500:	—

There are three possible explanations of the abundance anomalies:

(*a*) that the material in question has been accreted from the interstellar gas;

(*b*) that the material is a typical sample of material in the stellar core, where nuclear reactions have been taking place, and has been mixed to the surface;

(*c*) that the material has undergone nuclear reactions in the stellar atmosphere.

The first possibility can be dismissed immediately, since it would be applicable only if certain elements were accreted preferentially, or if the interstellar gas had these same abundance anomalies, both of which suggestions are highly improbable.

The second possibility might be the case if a source of neutrons were available in the stellar interior, since, as will be discussed later, the anomalies are mainly produced by neutron capture processes. Recent theoretical work on element synthesis has shown that to build heavy elements in this way the star must have reached an evolutionary stage at which it has a helium core and a hydrogen shell energy source. Stars at this stage must have reached the region of the red giants in the Hertzsprung–Russell diagram, or even a later evolutionary stage. On the other hand, there are a number of arguments which strongly suggest that the 'peculiar A' stars are relatively young, on or near the main sequence, and hence without large helium cores. For example, they occur in galactic clusters in which the main sequences extend up to the region in which they lie (Fowler, Burbidge and Burbidge [5]).

Thus we are left with possibility (*c*). If the process is a surface effect then the amount of nuclear activity which is demanded is directly related to the amount of mixing of the material in the stellar atmosphere with the material in the star's interior. A very interesting point is now brought to light. It seems probable that the normal main sequence A-type stars have very thin outer convective zones. The work of Rudkjöbing [6] and Vitense [7] shows that convection sets in up in the photosphere, but the convective zone will terminate where the temperature is under 20,000°, and the total thickness of the whole zone is then only $\sim 10^3$ km. Only in regions of great electromagnetic disturbance in the magnetic stars can we expect the mixing to greater depths to be important. The actual amount of the mixing will depend on the type of magnetic model that is assumed. It is of some interest to note that the models currently considered plausible for the sun by Bullard [8], by Parker [9], and by others, in which a toroidal field is convected to the surface to form sunspot pairs, is already in difficulties if it is applied to the magnetic stars, since they apparently have no deep convective envelopes. The total amount of material—the outer skin of the star—which must be processed by nuclear activity is somewhat uncertain. However, our original estimate that about $2{\cdot}5 \times 10^{28}$ g (corresponding to a total depth of 10^4 km with a mean density of 10^{-4} g/cm^3) has been contaminated by these processes still appears to be a reasonable one.

In previous work we supposed that the acceleration of ions by electromagnetic processes in stellar atmospheres gave rise to conditions which were suitable for element synthesis to take place. Two models were suggested, and it is a modification of these that we shall discuss here. In all cases, in order that synthesis of the observed heavy-element abundances can take place, a source of free neutrons must be available. Free neutrons can be produced only by (p, n), (α, n) and similar reactions. These involve threshold energies ~ 5 MeV for (α, n) reactions and proton energies in the range 3 MeV for C^{13} (p, n) to $18{\cdot}5$ MeV for C^{12} (p, n). Thus the problem of nuclear synthesis is that of accelerating a fairly large flux of protons and α particles to relatively low energies, and allowing them to interact locally. On the other hand, for the cosmic ray problem it is necessary to show that a fairly small flux of ions with energies $\geqslant 100$ MeV/nucleon is produced and ejected from a stellar atmosphere. The two processes are to some extent mutually exclusive at a particular level in the stellar atmosphere, since if a sufficiently large flux of high-energy protons and α particles is produced together with a low-energy component, spallation reactions of the high-energy particles will break up the nuclei which may have been built up in the neutron capture processes.

2. EVIDENCE CONCERNING PARTICLES ACCELERATED IN THE SOLAR ATMOSPHERE

In previous work we have suggested that the generation of the 'hot spots' in which neutrons are produced is due to a mechanism of the Swann type in which ions are accelerated in changing magnetic fields. Since our understanding of this mechanism is dependent on an adequate theory of magnetic stars, it is extremely difficult at present to estimate exactly how much magnetic activity is demanded to provide the energy for nuclear reactions. However, a number of observations of particles associated with solar activity suggest that an extrapolation from the sun to the 'peculiar A' magnetic stars is reasonable. The types of observation connected with the sun are then very significant.

Wild, Roberts, and Murray [10] have observed radio bursts which are sometimes associated with solar flares. They divide the bursts into three different types, each of which appears to be associated with a discrete range of velocities. Those associated with the highest velocities (type III bursts) are thought, from measurements of the frequency drift, to be caused by the coherent motion of fast particles upward in the solar atmosphere. These particles have velocities lying in the range $0 \cdot 1c$—$0 \cdot 3c$, which corresponds to proton energies in the range 5–50 MeV. These bursts have durations of 5–10 sec, and sometimes a cluster of bursts with a total duration of 1–2 min is observed.

Firor, Simpson, and Treiman [11] have made an attempt to estimate the total flux of particles emitted by the sun in the BeV range, using their observations of the low-energy solar cosmic-ray component. They find that the total flux is 2×10^{23} particles/sec/BeV at 4 BeV. Although there is some evidence for particles of much lower energies arising in the sun, both from auroral observations (Meinel and Fan [12]; Meinel [13]) and from balloon flights at the top of the earth's atmosphere (Meredith, van Allen, and Gottlieb [14]), no quantitative estimates of the average number of particles emitted has been made. However, if we assume that the particles accelerated follow a $1/E^3$ law (as is the case for an induction-type mechanism), then the results of Firor, Simpson, and Treiman suggest that about 10^{29} particles/sec are produced with energies in the range 4–14 MeV in the sun. Since only the particles which escape are observed by the Chicago group, this may be an underestimate.

Note added in proof

Recent results of Goldberg, Mohler and Müller (*Ap. J.* **127**, 302, 1958) show that deuterium probably builds up to approximately 10 % of the abundance of hydrogen in the material surrounding a solar flare such as that of 23 February 1956. This prompts us to abandon the conservative position taken in §5 below and to accept the possibility that some active regions do reach a temperature near 10^{10} degrees ($kT \sim 1$ MeV) with a neutron-to-proton ratio near 10 %. These neutrons diffuse into the surrounding material and can build up a 10 % concentration of deuterium in an amount of material equal to that in the active region. At the same time, each nucleus in the metal group will capture ~ 1 to 10 neutrons, if we assume that the surrounding material is raised in temperature to $\sim 10^5$ degrees where the metal group capture cross-sections become ~ 10 to 100 times that of hydrogen. In several processings of the surface material the observed over-abundances of the heavy elements will thus be synthesized. The deuterium will build up in the surface material to a figure at most equal to 10 %, because it is destroyed in re-cycling even in low-temperature spots (10⁷ to 10⁹ degrees) by the $D(p, \gamma)$ He^3, $D(d, n)$ He^3, and $D(d, p)$ T^3 $(\beta^- \nu^-)$ He^3 reactions. An eventual 10 % ratio for He^3 to H in the surface material is not at all out of the question; this was the value which was obtained from the analysis by Burbidge and Burbidge (*Ap. J.* **124**, 655, 1956) of the magnetic star 21 Aquilae.

We have been encouraged in the above point of view by the detailed analysis of Parker (*Phy. Rev.* **107**, 830, 1957) of the acceleration mechansim of cosmic rays in solar flares. The E^{-5} power law for the cosmic-ray energy distribution which he finds theoretically agrees approximately with that found experimentally for the 23 February 1956 flare (Meyer, Parker and Simpson, *Phys. Rev.* **104**, 768, 1956). It confirms our belief that spallation processes at high energy will not counteract heavy element build-up, especially since the high-energy acceleration takes place only in regions of relatively low density ($\rho \lesssim 10^{-12}$). The hot spots which we have discussed must occur in the regions below the flares and may reach the high temperatures (10^{10} degrees) required for copious neutron production ($n/p \sim 10$ %) by some kind of an extensive magnetic 'pinch' effect.

3. DURATION OF THE 'HOT SPOTS'

We suppose that the generation of 'hot spots' begins with the acceleration of an appreciable fraction of protons and other less abundant ions. The protons, unless they interact very rapidly with other nuclei, will lose their energy primarily to the electrons in the gas, which will radiate both by 'Bremsstrahlung' processes and through acceleration in the magnetic field. At a density of about 10^{-7} g/cm^3, the electrons will come into thermal equilibrium with the protons in times $\sim 10^{-5}$ seconds. The 'Bremsstrahlung' cross-section for the electrons, in the usual nomenclature (Heitler [15], ch. III), is given by

$$\sigma_{\rm rad} = \frac{dE_{\rm rad}}{dx}\frac{1}{nE} = \frac{5\cdot 5 r_0^2}{137} \text{ for } E = 1 \text{ MeV}$$

$$= 3 \times 10^{-27}\,\text{cm}^2 = 0\cdot 003 \text{ barn}. \tag{1}$$

The radiation lifetime for a 1 MeV electron under these conditions is given for $\sigma_{\rm rad}$ in barns by

$$\tau_{\rm rad} = \frac{2\cdot 2}{a\rho\sigma_{\rm rad} v}, \tag{2}$$

where a = relative abundance of protons = 1, the density $\rho = 3 \times 10^{-8}$ to 3×10^{-7} g/cm^3, and $v = 3 \times 10^{10}$ cm/sec. Thus $\tau_{\rm rad} = 0\cdot 1$ to 1 sec.

For the radiation in a magnetic field of strength H, if R is the radius of gyration of the electron, we have

$$\left(\frac{dE}{dt}\right)_{\text{rad}} = 3{\cdot}40 \times 10^{-16} H^4 R^2 \text{ MeV/sec}$$
$$\simeq 10^{-8} H^2 \text{ MeV/sec.} \tag{3}$$

Thus for a 1-MeV electron, if $dH/dt \gg 10^4$ gauss/sec, then radiation in the magnetic field will be the predominant mode of energy loss, while for fields such that $dH/dt \ll 10^4$ gauss/sec, 'Bremsstrahlung' will predominate.

In general it seems, therefore, that the time scale for the 'hot spots' must be $\gtrsim 1$ sec.

4. SIZES OF 'HOT SPOTS'

The dimensions of the regions in which particles are accelerated can be estimated theoretically only if the mechanism is fully understood. Failing this, we can appeal to the observational data on magnetic stars to place upper limits on the 'hot spot' dimension, as follows. We shall suppose that the sum of these areas present at any one time on the visible hemisphere of the star comprises a fraction of the disc characterized by the dimension a, and that these areas have a mean radiation temperature T_a. In following sections we shall consider accelerated proton fluxes which have some of the characteristics of a Maxwell–Boltzmann distribution of energies with $kT \sim 1$ MeV. The radiation losses from these particles are such that the radiation temperature $T_a \ll T$, but also it is probable that $T_a \gg T_{\text{eff}}$, where T_{eff}, the normal effective temperature of an A0-type star, is 11,000°.

The Rayleigh–Jeans approximation to Planck's law can be used to derive the radiative flux from the hot areas, i.e.

$$I_\lambda = 2kcT\lambda^{-4}. \tag{4}$$

This can be compared, at any wave-length λ, with the flux emitted by the undisturbed photosphere, calculated from Planck's law for a black body at 11,000°. Now we have the color measurements U-B and B-V by Provin [16] for a number of magnetic stars, where U, B, V are the stellar magnitudes on the photometric system of Johnson and Morgan, and represent filter-plate combinations with transmission maxima near the wave-lengths 3600, 4250, and 5300 Å respectively (Johnson [17]). Provin's colors for the 'peculiar A' stars in general indicate a slightly higher apparent temperature than that corresponding to the spectral type. If we postulate that this may be due, in part at least, to the presence of small 'hot spots' on the stellar surface, we may use Provin's color measurements, relative to the colors of a normal main sequence A0 star, to derive an order of magnitude for the upper limit to the characteristic dimension of the 'hot spots' present at any one time. Using the measures for α^2 CVn, as a typical magnetic 'peculiar A' star, we find that for $kT_a = 0{\cdot}1$, 1, and 10 KeV, $a = 3{\cdot}8 \times 10^9$, $1{\cdot}2 \times 10^9$, and $3{\cdot}8 \times 10^8$ cm, respectively (we have taken the stellar radius to be $2R_\odot$, and have neglected limb-darkening and fore-shortening of spot areas).

Provin also gives measures of the colour and luminosity variation through the period of magnetic variation of α^2 CVn. From these we may estimate the total allowable *change* in 'hot spot' dimension a. For $kT_a = 0{\cdot}1$, 1, and 10 KeV, we find that $\Delta a = 1{\cdot}3 \times 10^9$, $4{\cdot}0 \times 10^8$, and $1{\cdot}3 \times 10^8$ cm, respectively.

5. THE PRODUCTION OF NEUTRONS

At sufficiently high particle temperatures, neutrons can be produced by a multitude of (p, n) and (α, n) reactions, while if very high radiation temperatures could be developed, large-scale neutron production by inverse beta-decay processes would be possible. The usual equations of statistical equilibrium (R. H. Fowler [18], Chandrasekhar and Henrich [19]) suggest that if both the particle and radiation temperatures were about 10^{10} degrees, then a ratio of protons to neutrons of about 6 would be reached at equilibrium. However, this would demand that the mass density of radiation $\simeq 10^3$ g/cm^3. If such an energy could be supplied by the magnetic field, the local magnetic intensity would have to reach a value of $\sim 5 \times 10^{12}$ gauss, which appears to be very unlikely. Under the reasonable conditions suggested above, in which only a particle flux of high intensity is present, the main contribution to neutron production will be (p, n) reactions on the light nuclei. It is reasonable to assume that a neutron-proton ratio of the order of 10^{-3} to 10^{-2} will be built up, on the basis that each light nucleus will interact with protons or α particles to produce several neutrons.

6. THE DIFFUSION OF NEUTRONS AND THE FORMATION OF DEUTERIUM

After the free neutrons are produced, they will interact with hydrogen, and eventually they will either form deuterium in the spots while a small proportion will be captured by the elements in the Fe abundance peak, synthesizing heavier elements directly, or they will escape from the spots to be moderated and form deuterium in the quiescent regions. The diffusion length L_D for neutrons can be calculated as follows. We have (Feld [20])

$$L_D = \left(\frac{l_{\mathrm{trans}} \times l_{\mathrm{cap}}}{3}\right)^{1/2},$$

where l_{trans} and l_{cap} are the transport length and the capture length, respectively. In hydrogen $\sigma_{\mathrm{trans}} = \sigma_{\mathrm{np}}/3$, where σ_{np} is the neutron-proton scattering cross-section. Thus

$$L_D = (l_{\mathrm{np}} l_{\mathrm{cap}})^{1/2}.$$

At energies of 1–2 MeV, $\sigma_{\mathrm{np}} \simeq 3$ barns (Blatt and Weisskopf [21]), and σ_{cap} on the proton-rich isotopes of C, N, O, and Ne is $\sigma_{\mathrm{geom}} \simeq 0{\cdot}33$ barn.

Now

$$l = \frac{2{\cdot}2}{a\rho\sigma},$$

where σ is in barns, and a is the abundance relative to hydrogen of the interacting nucleus. Since $a(\mathrm{C, N, O, Ne}) \simeq 2 \times 10^{-3}$,

$$L_D \rho = 48.$$

If $\rho = 10^{-7}$ g/cm^3, then $L_D = 4{\cdot}8 \times 10^8$ cm. Thus for spot radii $< 5 \times 10^8$ cm the majority of the neutrons moving in levels parallel to the star's surface will diffuse out of the hot areas before being captured, and will then be thermalized and form deuterium. If the total 'hot spot' area considered in § 4 is an average area made up of a large number of smaller areas, then the neutrons will inevitably diffuse out before being captured.

The vertical diffusion problem is more complicated, but we have supposed that the depth of the 'hot spots' ~ 10^8 cm, and calculation of the scale height for an A-type star suggests that vertical diffusion of the neutrons both inward and outward away from the 'hot spot' will be possible. There is uncertainty, however, in the effective depth of the 'hot spot'.

It thus appears that following their production, the neutrons will escape from the accelerated regions into the quiescent atmosphere, where they will be thermalized and rapidly captured by protons to form deuterium which will be continuously built up on the surface until it in turn is depleted in the 'hot spots'.

7. THE SYNTHESIS OF THE HEAVY ELEMENTS AND He^3 BY REACTIONS BETWEEN PROTONS, NEUTRONS, DEUTERONS, AND THE METALS

In order to build the heavy elements to the over-abundances shown in Table 1, about 20 neutrons per Fe nucleus are demanded (Fowler *et al.* [5]). It is first necessary to decide whether the spots which are already required to provide the neutrons will be capable of synthesizing elements by means of the deuterium already present in material which has been produced in previous spot activity. If $kT \simeq 1$ MeV, we showed (Fowler *et al.* [5]) that if sufficient time were available the neutrons would eventually be captured by the metallic elements; the mean number N of neutrons captured per Fe nucleus was given by

$$N = 1\cdot5 \rho t \times 10^4.$$

At $\rho = 10^{-7}$ g/cm^3, if $t = 1$ sec, $N = 1\cdot5 \times 10^{-3}$, and in order that 20 neutrons should be captured per Fe nucleus, this would mean that each gram of material would have to be processed $\sim 10^4$ times. However, under these conditions further neutrons would be produced in each spot at the same time, and the final deuterium abundance in the surface would be about thirteen times the abundance of hydrogen. This result is completely in contradiction with observation, and it is clear, therefore, that a second type of 'hot spot' must be responsible for the synthesis. The characteristic of this second type of acceleration is that it must produce a flux of protons which contains practically no particles of high enough energy for neutron production to take place by (p, n) or (α, n) reactions. The neutrons are then produced only by the $H(\alpha, n)\ 2H$ reaction from the deutrons which have been produced in other regions. A Maxwell–Boltzmann distribution with $kT \sim 0\cdot2$ MeV or a flux having $N(E) \propto E^{-n}$ with a sharp cut-off near $E = 6$ MeV are possible cases to be considered. Thus in spots in which synthesis takes place, the reactions which we have to consider are those involving protons, neutrons, and deutrons: $H(d, \gamma)$ He^3, $H(d, n)\ 2H$, $H(n, \gamma)\ D$, and the synthesizing reactions on the heavy elements which are either (n, γ) capture reactions, or (d, p) stripping reactions at low energy (Oppenheimer–Philipps processes).

The protons with very low energies will only transform the deuterium into He^3 by the $H(d, \gamma)$ He^3 reaction. The cross-section for this has been measured by Fowler, Lauritsen, and Tollestrup [22] to be given by

$$\sigma = 0\cdot74 E_p^{0\cdot72} \times 10^{-5} \text{ barn}.$$

Above the threshold for the $H(d, n)\ 2H$ reaction the cross-section is about 0·1 to 1 barn, so that the mean lifetime for the break-up of the deuteron $\tau_d =$ 0·002 to 0·02 sec, where we have put $\rho = 10^{-7}$ g/cm^3, $v = 3 \times 10^9$ cm/sec. On the other hand the cross-section for the $H(n, \gamma)\ D$ reaction is only about 10^{-4}–10^{-5} barn at these energies, so that the mean lifetime for the formation of deuterium is about 100–1000 sec. Thus in the duration of the spot, a large proportion of the deuterium will be disintegrated. Thus the majority of the heavy-element synthesis will take place through the capture of free neutrons, though there will be a very small contribution from Oppenheimer–

Philipps reactions, which have a cross-section ~ 0·1 barn with an energy dependence roughly proportional to E^2 in the energy range 2 MeV $\leqslant E \leqslant$ 8 MeV for the metallic elements (Peaslee [23]).

The cross-section for the (n, γ) reactions on heavy nuclei have been given in our previous paper, and we have shown earlier in this section that in order that about 20 neutrons per Fe nucleus should be captured on the average, each gram of material would have to be processed 10^4 times. The ratio r of the rates of the reactions which synthesize He^3 from deuterium and synthesize heavy elements by free neutron capture is given by

$$r = \frac{a_p a_D \int_{E_1}^{E_2} \sigma(d, \gamma)\ N(E_p)\ dE}{a_n a_{Fe} \int_{E_3}^{E_4} \sigma(n, \gamma)\ N(E_n)\ dE}. \tag{9}$$

Here we have supposed that $N(E)$ is a function representing the primary energy spectrum of accelerated particles. We shall suppose that the neutrons released by the $H(d, n)\ 2H$ reaction attain a similar energy spectrum. Also, since the neutrons are freed from the deuterium in a time which is short compared with the life-time of the spot, we can suppose that the number of neutrons present in the spectrum of accelerated particles is equivalent to the number of deuterons which would be present in the energy range above the neutron production threshold, $E_3 - E_4$. Thus we may put $a_n = a_D$ in Eq. (9).

An estimate of the numerical value of this ratio can be made by using the formula given by Fowler *et al.* [22] for $\sigma(d, \gamma)$ and by writing

$$\sigma(n, \gamma) = 4{\cdot}8 \times 10^{-3} E^{-0{\cdot}5}$$

(cf. Fowler *et al.* [5]). If we put $N(E) \sim E^{-1}, E^{-2}, E^{-3}$, and set $E_1 = 0{\cdot}5$ MeV, $E_2 = E_3 = 2{\cdot}5$ MeV, $E_4 = 6$ MeV, we find that $r \simeq 270$, 800, and 3000, respectively. Thus, in order that on the average each Fe nucleus shall capture about 20 neutrons, this mechanism demands that $20r$ neutrons in the form of deuterium should be available, and the majority of this will form He^3. The total abundance of He^3 which is in equilibrium with the over-abundant heavy elements will be given by

$$\frac{a\mathrm{He}^3}{a_p} = 20r \times 2{\cdot}2 \times 10^{-5},$$

and if $r \simeq 200$

$$\frac{a\mathrm{He}^3}{a_p} \simeq 10^{-1}.$$

He^3 will be destroyed mainly by the He^3 (He^3, $2p$) He^4 reaction, but the effect of this will be small as compared with the $H(d, \gamma)$ He^3 reaction. Thus it appears that the He^3 abundance may easily build up to a value very close to that of He^4 (the $a\mathrm{He}^4/a_p$ ratio in normal stars $\sim 10^{-1}$). The a_D/a_p ratio (see note on p. 226) will be of the same order as the $a\mathrm{He}^3/a_p$ ratio. The production of He^3 depends very sensitively on the form of the spectrum of the accelerated particles. If, for example, the spectrum has the Maxwell–Boltmann form, so that $N(E) \propto E^{1/2} \exp(-E/kT)$, a value of $kT \sim 0{\cdot}2$ MeV will lead to practically all of the deuterium being converted into He^3, with very little synthesis of the heavy elements. In fact, unless the energy spectrum is fairly flat over the energy range which we have considered, the ratio of the amount of He^3 produced to that of the heavy elements will be very large and, to give the required production of the heavy elements, will lead to an amount of He^3 incompatible with the observed total abundance of He ($He^3 + He^4$). If synthesis took place following a burst of mono-energetic particles, then either only production of He^3, or only production of the heavy elements, would occur, depending on whether the particle energy was below or above the threshold for the $H(d, n)\ 2H$ reaction.

Thus a situation in which the ratio $a\mathrm{He}^3$/normal $a\mathrm{He}^4$ becomes greater than unity, and in which little synthesis of the heavy elements has occurred, may easily arise. In this case a magnetic star might be expected to show an apparent over-abundance of He, which would be detectable as He^3 if the effect of the isotopic shift on the spectrum lines could be measured. The magnetic star 21 Aquilae has moderately strong lines of He, and lines of Si II which are too strong to be compatible with them, although an abundance determination has not yet been carried out. Lines of Eu II and the other rare earths are not visible. The isotope shift between He^3 and He^4 should, if He^3 is present, be detectable by a wave-length shift of the spectrum lines $\lambda\lambda$ 4388, 4144, and 4009, for which the difference between the two isotopes is $\Delta\lambda \simeq 0{\cdot}3$ Å, relative to the lines at $\lambda\lambda$ 4471, 4121, and 4026, for which $\Delta\lambda \simeq 0{\cdot}1$ Å (Greenstein [24]; Fred *et al.* [25]). Preliminary results for 21 Aql, using plates obtained by H. W. Babcock and one obtained by Burbidge and Burbidge [26] indicate that such a shift may actually be present and may indicate an abundance of He^3 comparable to that of He^4.

8. THE AMOUNT OF ACTIVITY DEMANDED FOR SYNTHESIS

The amount of activity demanded on the stellar surface to produce the observed heavy-element anomalies can be estimated as follows. Since only a fraction of the neutrons may be available for heavy-element synthesis, the primary consideration is that enough neutrons should be produced to build He^3 through the sequence of events outlined in § 7. We have earlier estimated that the total amount of material which has been contaminated has a mass of $\sim 2 \cdot 5 \times 10^{28}$ g. Thus, if the He^3/H ratio is built up to about 10^{-1}, and if a similar ratio of D/H to that for He^3/H is assumed, the total number of neutrons which must be produced by (p, n) reactions is about 5×10^{51}. If the neutrons are produced mainly through the (p, n) reactions on light nuclei in spots in which the particle temperature is given by $kT = 1$ MeV, the sum of whose areas is such that the total effective radius is 10^9 cm, with a depth of 10^8 cm, and a mean density of 10^{-7} g/cc, then the total mass involved in each sum of spot areas present at any one time is about 3×10^{19} g, and the number of neutrons produced is $\sim 2 \times 10^{40}$. Thus, in order to produce the total neutrons required, about $2 \cdot 5 \times 10^{11}$ such spots or sets of spots are required. If the total time-scale available is $\sim 10^{16}$ sec (cf. Fowler *et al.* [5]), then the frequency of neutron-producing spots is about one (or one set) every 11 hr.

On the other hand, if the spots in which the synthesis takes place involve the same mass as those in which the neutrons are produced, then the number of spots demanded to process the surface material once is $\sim 10^9$. However, we have shown earlier that each gram of material must be processed about 10^4 times. Thus the total number of synthesizing spots must be about 10^{13}. Hence the frequency of these spots is about one every 10^3 sec.

Some comparison can be made between this activity and that on the sun. In § 2 we estimated, from the work of Firor *et al.* [11], that a representative number of particles in the MeV range was $\sim 10^{29}$/sec. Thus in 10^{16} sec about 10^{45} particles will have been accelerated. If the efficiency of production of neutrons is only about $\sim 1\%$, this means that a magnetic star must have accelerated $\sim 5 \times 10^8$ times as many particles as the sun. It is difficult to devise theoretical methods of making comparisons, but if the activity is in any way related to the relative amounts of magnetic energy available, it is interesting to note that, since the mean solar field is ~ 1 gauss and that in magnetic stars is $\sim 10^4$ gauss, the ratio of surface magnetic energies in the two stars is $\sim 10^8$.

The estimates which have been made here are necessarily very uncertain. In particular, our concept of 'hot spots' may be superseded by models based on the particle fluxes responsible for the solar bursts observed by Wild *et al.* Thus it may be that the atmosphere of a magnetic star is continuously in eruption with large numbers of isolated small-scale flares taking place continuously over the surface.

9. CONCLUSION

The conditions for surface nuclear reactions which have been described differ from our previous ideas in a number of ways. In particular, by taking into account the radiation losses following particle acceleration, which we previously neglected, we have found that the time scale involved in discrete events is only of the order of seconds. The mode of neutron production, principally through (p, n) reactions on light nuclei, is the same as that proposed previously in our model (b), and the synthesis is still believed to take place through free neutron capture processes, but these will occur after the neutrons have been freed from the deuterium in which they customarily reside. Necessarily associated with this synthesis will be the production of He^3 by the $H(d, \gamma)$ He^3 reaction. The ratio between the two rates is such that we may find, in stars with anomalous heavy-element abundances, an amount of He^3 equal to the normal He^4 abundance. In equilibrium a similar amount of deuterium will also be present; it is still not certain what is the amount of deuterium on the star's surface which could definitely be detected observationally.

The details of the over-abundance ratios, and in particular the anomalies in certain elements such as Ba, still remain largely unexplained.

The mechanism of acceleration of the particles is still not understood in any detail, and we have been forced to appeal to the solar observations. Accelerations of the Swann type, the neutral-point type, or plasma mechanisms, may be effective.

Finally we wish to acknowledge the many helpful discussions on all aspects of this problem which we have had with Professor R. F. Christy.

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Discussion

Biermann: There are fairly strong reasons which indicate that the acceleration processes should take place in high layers of the stellar atmosphere. In contrast, the nuclear reactions take place in any case in rather deep layers, as considered by Dr Burbidge. Thereby the efficiency of the whole process is limited very severely by energy losses due to thermal electrons. The average energy per unit mass may necessarily be confined to the range 10–20 or 25 MeV on account of the preponderance of the spectrum above this energy range. Carrying out more detailed estimates (which may be found in a paper in the *Z. Astrophys.* **41**, 46, 1956), it is found that only if everything combines in the most favorable way can the process be both operative and effective in the sense of Fowler, Burbidge and Burbidge.

Burbidge: I agree that the problem is very difficult but I think this must be the most plausible one among the three possibilities that were discussed.

Spitzer: Is it really so difficult to get rid of the deuterium reaction? Heating the material up to moderate temperature—some 10 keV or more—will dispose of most of the deuterium by the D–D reaction, producing additional neutrons in the process. The cross-section of this process is known to be large.

Burbidge: I do not know but I think that since we only have a small amount of deuterium the rate of destruction by D–D reactions might be rather small.

Severny: Did you actually find He^3 in stellar spectra?

Burbidge: We believe so, although the difference between He^3 and He^4 lines is very small, and a distinction is difficult to make.