are known to exist in the stratosphere. It would be extremely interesting to investigate the isotopic composition of oxygen in the stratosphere as well as from various geographical locations such as the arctic and the tropics. It might be possible to follow large-scale air currents in this way because, from all we know now, the photosynthesis reaction of the oceans is delivering to the atmosphere oxygen having a different isotopic composition from that already present. Similarly, the stratospheric oxygen may have an isotopic composition different from the oxygen in contact with the tropical oceans. The maximum expected difference between stratospheric and photosynthetic oxygen is 33 parts per mil of which the error of measurement is estimated as 1 part per mil.

We come finally to the thought that if oxygen exchange in the stratosphere is significant, then synthesis of oxygen in the stratosphere may also be significant, and that the total abundance of free oxygen in the atmosphere may be slowly increasing. In other words, it would appear that oxygen has a future as well as a past and present history.

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(For references see column 2, p. 96.)

On the Origin of the Chemical Elements

D. ter Haar[1]

Department of Physics, Purdue University

IN RECENT YEARS MANY ATTEMPTS have been made to explain the observed abundance of the chemical elements and their isotopes. A survey of papers on this subject will be presented in a forthcoming paper (*4*). In this article, an attempt will be made to connect these theories with the general cosmogony developed by von Weizsäcker (*9*), not by offering a complete and quantitative theory, but rather by sketching a possible way of combining ideas expressed by other authors into a theory which may, perhaps, be more satisfactory than the existing ones.[2] The limitations of earlier theories are considered in the survey paper (*4*) mentioned earlier.

The idea is to eliminate one of von Weizsäcker's initial conditions, on the one hand, and to suggest possible initial steps for the theories of van Albada (*1*), Beskow and Treffenberg (*2*), and Mayer and Teller (*7*). In von Weizsäcker's cosmogony the universe is, at the beginning of the present epoch, filled with a turbulent gas. The origin of this gas and its turbulence is assumed to be a problem lying outside the scope of this cosmogony. Von Weizsäcker further assumes, however, that the composition of this gas is the same as the present composition of interstellar gas, or stellar material. It may be sufficient, however, to assume this gas to consist of hydrogen only, thus simplifying the initial conditions of von Weizsäcker's cosmogony. Expressed differently, the solution of the problem of the origin of the chemical elements, other than hydrogen, is thus brought into the present epoch. By the "present epoch," we shall understand the period often referred to as the age of the universe. Following present ideas about the age of the universe, we shall put it at between 10^9 and 10^{10} years (*3, 4, 8*).

As was shown by von Weizsäcker, in the gas filling the universe, concentrations of mass and finally gaseous bodies with masses of the order of stellar masses will be formed. Due to the conservation of angular momentum, these bodies will be rotating fast. In the beginning the energy of these stars will be provided by gravitational energy, and later the deuterium reaction ($H + H \rightarrow D$) will set in. When the densities and central temperatures have become greater, the von Weizsäcker-Bethe carbon-nitrogen cycle will start. (The necessary carbon nuclei will have been formed by nuclear reactions in the way, for instance, discussed by Bethe.) When all the hydrogen has been used, the star will collapse. The development described by Hoyle (*5*) will follow. Of particular interest are those stars which have not yet lost their

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[1] The author would like to express his thanks to Drs. Mayer and Teller for a discussion of the subject matter of their paper (7) and an opportunity to see the manuscript prior to publication. The material was presented at the Solvay Congress in 1948 and, for publication, will be extended to include a short survey of the older theories. The author is also grateful to Dr. von Weizsäcker for the opportunity to read his paper (*10*) prior to publication.

[2] Some of the ideas presented in this paper are similar to ideas expressed by van Albada and Hoyle.

rotation when their hydrogen is used up. At the interior of these stars heavy nuclei will be formed in a thermodynamical equilibrium. The most reliable analysis of the composition of the interior of such a star can probably be found in Beskow and Treffenberg's paper (*2*). The breakup of the star probably will be rapid, as has been emphasized by van Albada (*1*) and Hoyle (*5*), and in this way the heavy nuclei will be distributed over space.

These heavy nuclei will not, however, be the nuclei found now. As was stressed by van Albada (*1*), the ratio of protons to neutrons will be much lower for these nuclei than for stable nuclei found in nature. Radioactive processes will reduce these nuclei to stable nuclei. Mayer and Teller (*7*) have shown that these radioactive processes will lead to isotopic abundances in qualitative agreement with those observed. In this way, the final result of the processes described here would be a universe filled with chemical elements with about the right isotopic abundances. The advantage of the present theory over that of Mayer and Teller is that we are able to account for the neutron-rich heavy nuclei in a natural way, while Mayer and Teller have to introduce their "polyneutron," the origin of which remains an open question. Also, the present theory has the advantage of considering the total amount of elements in the universe, instead of only single concentrations of matter with masses of the order of stellar masses, as was done by previous authors.

Up to now, the picture given in the present paper has been purely qualitative. Let us try to indicate how it can be changed into a more quantitative theory. It will be shown, especially, that there is no reason as yet not to accept this solution, since it gives satisfactorily the ratio between the abundances of hydrogen and heavy elements. Expressed differently, the processes indicated here are probably sufficiently frequent to account for the present distribution of elements.

It is still impossible to use hydrodynamical arguments to predict the distribution function, $f(M)$, of stars over the various masses. It is possible, however, to use for this function the observational data of Kuiper (*6*). On the other hand, it is well known that stars with masses larger than the sun, which belong to an earlier spectral class, cannot have lived during the whole of the present epoch. Thus, whereas dG-stars, which are observed now, can have been formed at any moment during the last 10^{10} years, B-stars must have been formed in the last 10^8 to 10^9 years (*8*). B-stars which were formed earlier have long ago burned their energy and exploded. These stars (O, B, perhaps A) must, therefore, have been responsible for the presence of heavy elements. According to Kuiper's figures, these stars are, at most, 1 per cent of the total number of stars. However, due to their large masses, they may possess as much as 5 per cent of the total mass of the stars.

If we wish to estimate how large a percentage of the mass of the universe has been involved in the processes leading to the formation of heavy elements, we have to take into account three factors: (a) the present percentage of early-type stars is artificially lowered by their short life; (b) only part of these stars will give birth to heavy elements; the explosion may occur before the central density is sufficiently high; and (c) about one half of the mass of the universe is not stellar, but interstellar material. Taking these factors into account we might safely conclude that at least 1 per cent of the total mass of the universe must have undergone the processes described above.

If we now compare the abundances found by Beskow and Treffenberg (*2*) with the observed abundances, it is seen immediately that with 1 per cent of the mass of the universe giving rise to heavy elements, the formation of heavy elements has been sufficiently frequent to explain their abundances. The high abundance of helium can possibly be explained either by the α-radioactivity of the very heavy elements or by an evaporation from "normal" stars, where helium is continuously formed. The fact that the observed abundances of light elements (C, N, O) are so much higher than in Beskow and Treffenberg's theory may well be due to the possibility that many stars may have been broken up before the formation of heavy elements started (cf. Hoyle, *5*, and van Albada, *1*).

If a quantitative law for the distribution function $f(M)$ and also for the relation between angular momentum and mass of a star was known, it would be possible to calculate more quantitatively both how large a fraction of the mass of the universe had been involved in the various processes and how large a fraction of the O-, B-, and A-stars were broken up before attaining high central densities. It is satisfactory that preliminary considerations by von Weizsäcker (*10*) show that the observed correlation between spectral type and rotation, which points to a possible early rotational instability of O-, B-, and A-stars, can be understood, at least qualitatively.

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