COSMICAL ALCHEMY

Combined research from four fields of science—physics, astrophysics, astronomy and geochemistry—leads to a new theory of the synthesis of the elements in stars

by MARGARET and GEOFFREY BURBIDGE

FOR MANY YEARS physicists and astronomers have speculated on the origin of the chemical elements. In every case they have tried to understand the conditions under which all of the elements could be built up out of the fundamental building blocks, which are protons, neutrons and electromagnetic radiation. In the last three or four years many ideas have come from staff members or visitors at Caltech. These suggest that the element-building processes have gone on, and are continuously going on, in the interiors of stars.

It has been known since the classical work of Hans Bethe in 1938 that the energy radiated by stars is released in the stellar core by the conversion of hydrogen into helium through the carbon cycle or the proton-proton cycle. From 1950 to 1952 R. N. Hall, E. J. Woodbury, and A. W. Schardt, working as graduate students in the Kellogg Radiation Laboratory under Drs. W. A. Fowler and C. C. Lauritsen, made measurements on the carbon cycle reaction probabilities at low energies and experimentally confirmed Bethe's ideas.

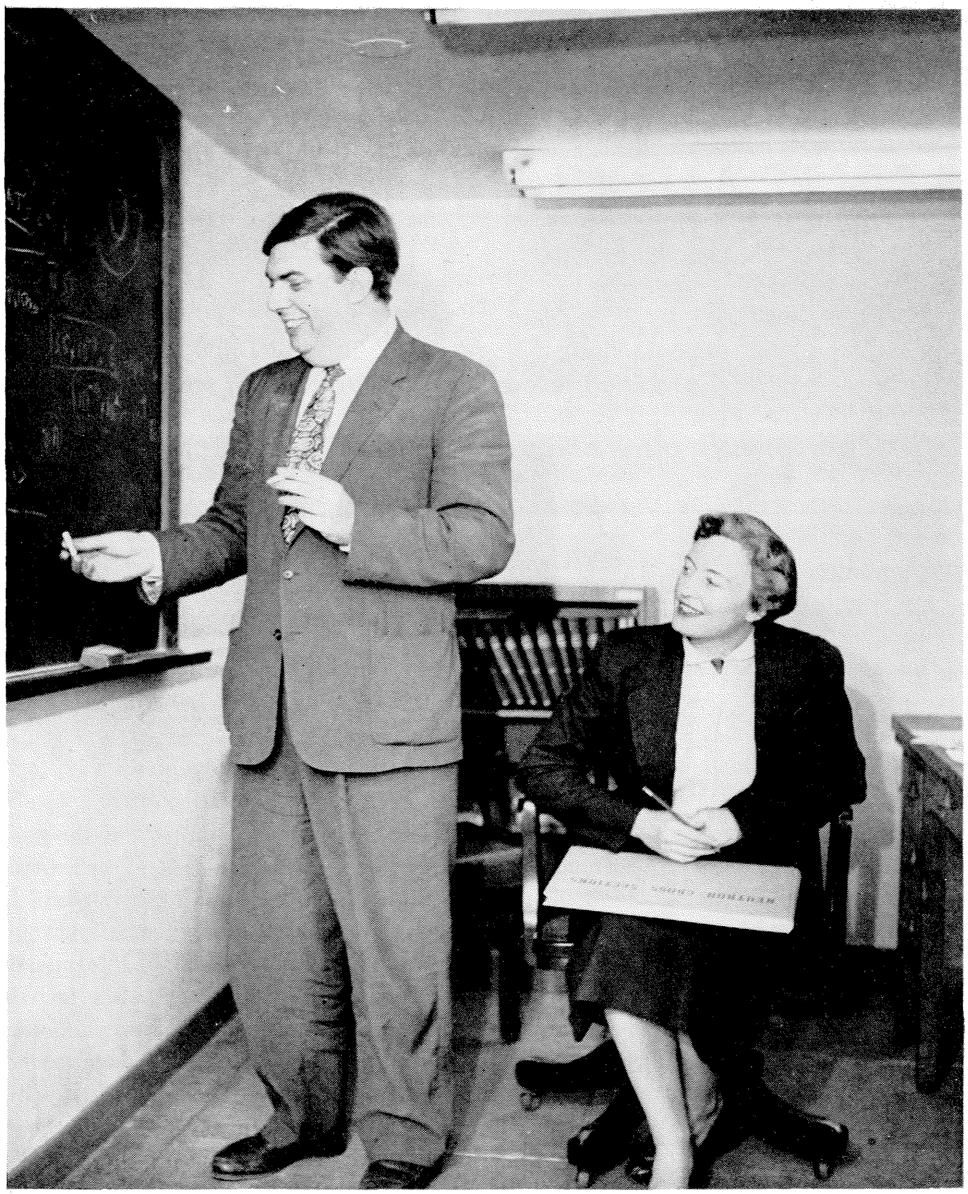
Until recently, reactions producing elements heavier than helium were not considered to be possible in stars. However, in 1949 Dr. Alvin Tollestrup, now assistant professor of physics in Caltech's Synchrotron Laboratory, investigated, with Fowler and Lauritsen, the properties of beryllium 8, an isotope of beryllium of mass approximately eight times that of the proton or neutron, which does not exist in nature and is therefore presumably unstable but which can be produced momentarily in the laboratory. He showed that the beryllium 8 was indeed unstable but broke up into two helium 4 nuclei (alpha-particles) with the release of only 100 kilo-electron volts of energy.

This result laid the groundwork for Dr. E. E. Salpeter of Cornell University, on a visit to Caltech in the summer of 1951, to show theoretically that if sufficiently high temperatures (about 100 million degrees) could be reached in the helium cores of stars, a small but not negligible amount of beryllium 8 would be formed in equilibrium with the helium. Before breaking up, the beryllium 8 has a chance to capture another alpha-particle to produce a stable carbon 12 nucleus. Then further alpha-particles would be captured by the carbon to produce, successively, oxygen, neon, magnesium and silicon.

Since beryllium 8 exists only for a very short time it cannot be bombarded in the laboratory as can stable nuclei. However, at the present time an experiment is underway in the Kellogg Radiation Laboratory in which the break-up of an excited carbon 12 into beryllium 8 and an alpha-particle and thus eventually into three alpha-particles is observed. This indicates, by the general laws concerning the reversibility of physical reactions that the process by which alpha-particles form carbon 12 will take place in stars under appropriate conditions. It appears, therefore, that some of the lightest and most abundant elements can be produced by helium reactions.

To build the rest of the light elements, like fluorine, sodium and aluminum, we need to suppose that the carbon, oxygen and other light elements will interact with protons and alpha-particles. The consequences of such activity have been worked out by Fred Hoyle, Fellow of St. John's College, Cambridge — when he was visiting professor at Caltech in 1953 — and by W. A. Fowler—when he was visiting Cambridge as Fulbright professor in 1954-55—with Margaret and Geoffrey Burbidge at the Cavendish Laboratory, University of Cambridge.

It may be asked at this stage whether there is any



Margaret and Geoffrey Burbidge, from Cavendish Laboratory at the University of Cambridge, England, are at Caltech this year to continue their work with Dr. W. A. Fowler on the astrophysical processes by which elements are produced in stars.

observational evidence that there are stars which have central temperatures hot enough for such reactions to take place. Recent work on the evolution of the stars suggests that the red giant stars, which are colossal nuclear furnaces, and which have diameters many times larger than that of the sun, but whose surface temperatures are cooler than the sun's, do have conditions near their centers which are suitable.

Now, in order to build elements heavier than those already mentioned, more complicated processes have to be introduced. Hoyle has suggested that the elements from silicon right up to titanium may be built by the interactions of charged nuclei, like helium and carbon. However, it is almost certain that this is not the whole story.

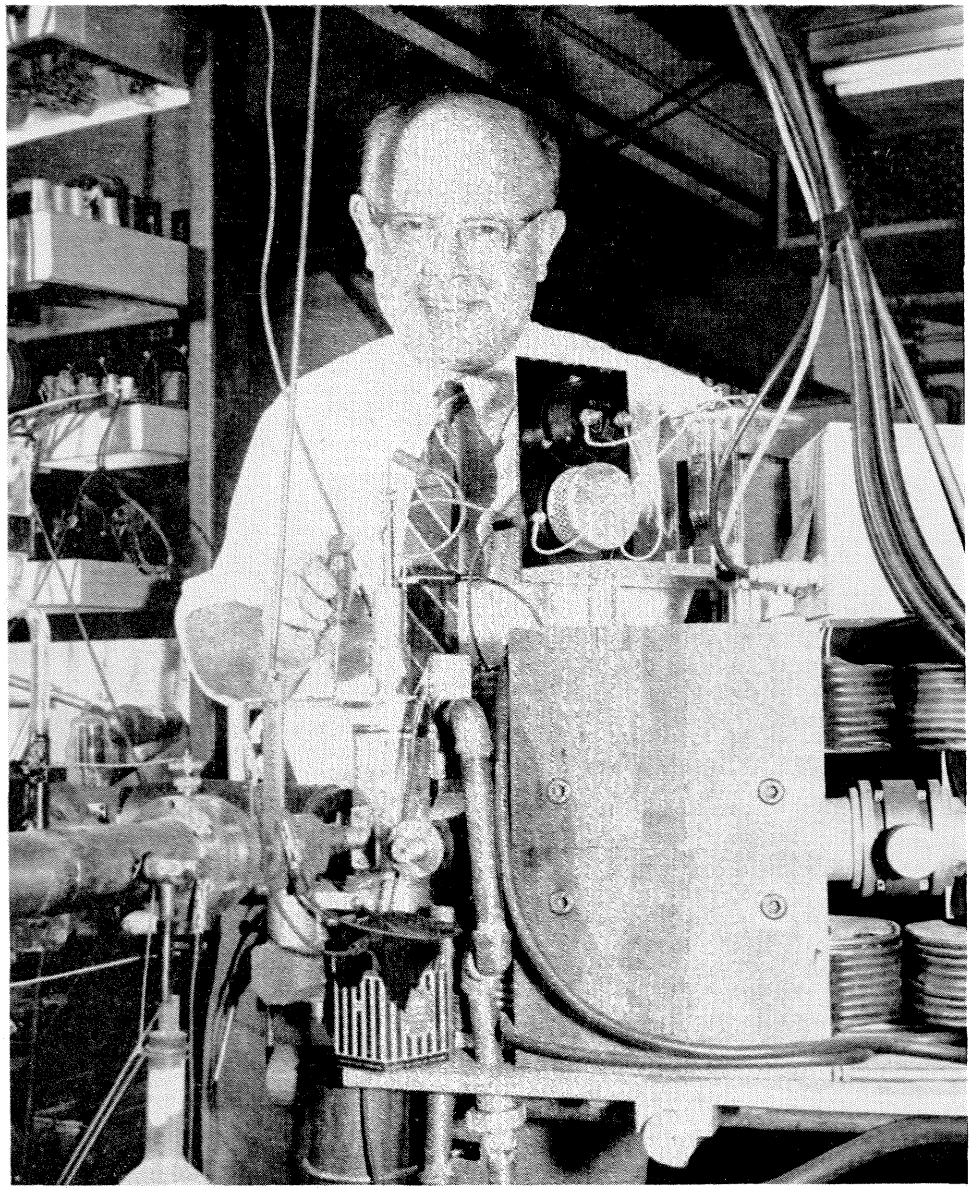
In this connection, a very important step forward was made by Dr. A. G. W. Cameron of the Chalk River Atomic Energy Establishment in Canada, who suggested that if a carbon 13 nucleus captures an alpha-particle, the end product would be an oxygen nucleus together with a neutron. Thus, if this process goes on inside red giant stars, a source of neutrons will be produced.

These neutrons will very rapidly reach equilibrium with the hot gas in the star's interior and then they will be captured by the other elements. If a number of successive capture processes take place on the same nucleus, we can easily see that we shall build heavier and heavier elements. There are some measurements of the probabilities of capture of neutrons by different nuclei, and it is possible to calculate what will be the relative numbers of nuclei of different kinds which are produced by such a process.

Such a calculation suggests that maybe not enough neutrons are produced by Cameron's process to build the elements to the required levels, and Fowler and the Burbidges have therefore suggested, as an alternative, a similar process in which a neon 21 nucleus interacts with a helium nucleus, giving a magnesium 24 nucleus and a neutron.

Under suitable conditions this process will provide

W. A. Fowler, professor of physics, at the observation station of the two-million-volt accelerator in the Kellogg Radiation Laboratory. Evidence for the formation of carbon from three helium nuclei has recently been found with this equipment.



more neutrons than that described by Cameron. So neutron sources of this sort may arise inside stars which have already built either the light elements up to neon or silicon, or in stars which already contain iron and the elements near to it in the periodic table. If the stars have only got the light elements, these then will capture all of the neutrons, and the intermediate elements between neon and titanium will be built.

Calculations by Fowler and the Burbidges suggest that a large proportion of the elements in this region of the periodic table will be built by this process, though some may also be built by the charged particle reactions described by Hoyle. If, on the other hand, the star already contains the metals in its core, these will capture all of the neutrons and the very heavy elements from nickel to lead will be built up.

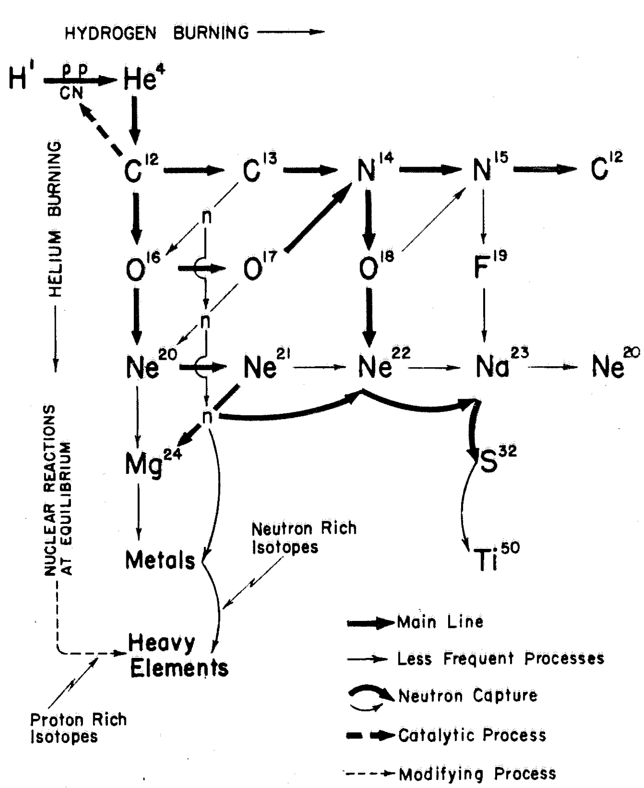
When the cosmical abundances of all of the elements are collected together and plotted on a curve of relative numbers of atoms against their atomic weight, as has been done, for example, by Dr. Harrison Brown, Caltech professor of geochemistry, this curve shows a large peak for the atoms in the metallic group, with the maximum at iron.

This peak cannot be explained by any of the processes described so far. To explain it, Fred Hoyle has suggested that the star contracts again and so its temperature and density rapidly increase. When a temperature of about five billion degrees is attained the nuclei reach equilibrium, one with another, and calculations made by Hoyle suggest that most of the matter in the core of the star will be transmuted into atoms of iron and other elements close to it, so that in fact the central region of the star is simply an iron ball.

More detailed calculations along these lines are now being made at Caltech. In the diagram at the top of page 20, the various reactions which have been described by Fowler and the Burbidges are shown schematically.

Thus the various steps of this argument suggest that the majority of the elements between hydrogen and lead can be processed over very long times in the interiors

Synthesis of the Elements in Stars



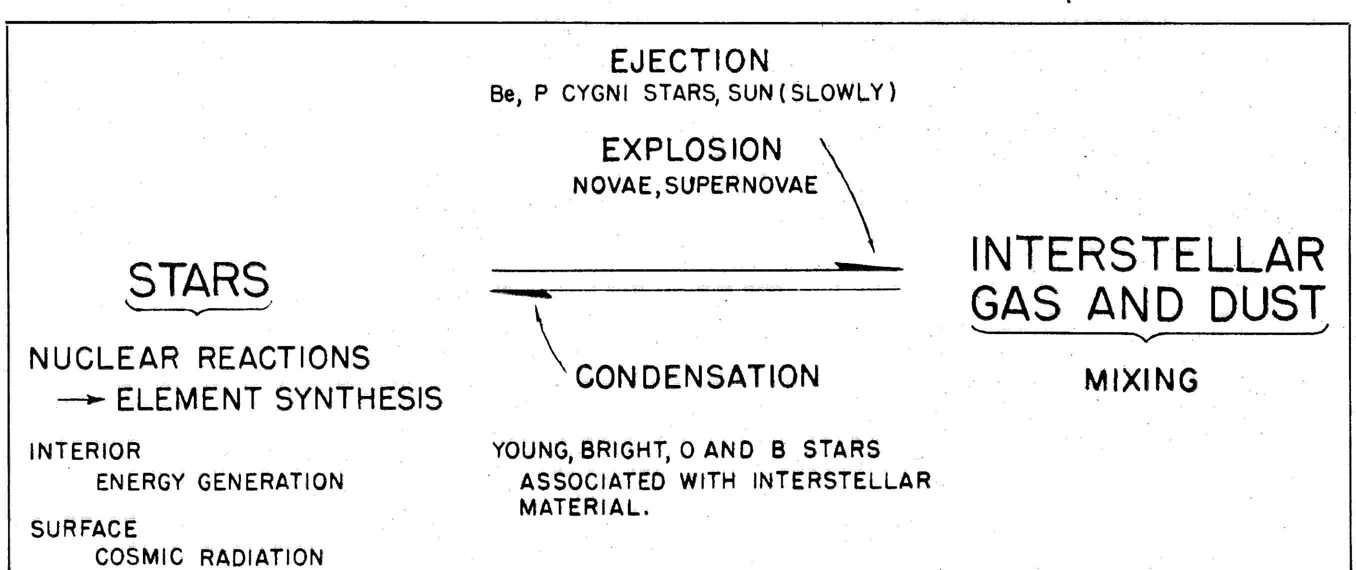
of stars. Observational evidence in support of this type of theory has been found by astronomers who have analyzed the spectra of stars of different brightnesses, masses and ages, and they find evidence in them of differences in chemical composition. Much of the work along these lines has been carried out by Dr. and Mrs. Martin Schwarzschild of Princeton and Dr. L. H. Aller of the University of Michigan—when they were visiting the Mt. Wilson Observatory—by Dr. Jesse L. Greenstein and Dr. Paul Merrill of Mt. Wilson and Palomar and Caltech, by the Burbidges and Dr. W. P. Bidelman—when they were working at the McDonald Observatory, and the Universities of Chicago and Texas—and by others.

Some stars show large amounts of carbon, and the ratio of the numbers of carbon 12 and carbon 13 atoms in them is different from the ratio in normal stars, suggesting that the processes involving the building of carbon have been going on in there. Greenstein has made contributions on this subject, and also on the abundance of lithium and beryllium in the sun, which are of importance in considering the depth to which the surface material of the sun is stirred up and mixed inward by convection currents.

Other stars in the red giant stage show apparently large abundances of the very heavy elements, suggesting that in them the neutron capture processes are going on. The discovery of technetium in some of these stars by Merrill is an extremely good pointer in this direction. This element is unstable and has a half-life against decay of about 200,000 years. It has been produced in the laboratory by bombarding molybdenum with neutrons from a nuclear pile. Thus when it is found in stars this is a good indication that it is being produced in their interiors by neutron bombardment and that it is traveling to the surface in a time which will be less than 200,000 years. Also, some of the older stars appear to have proportionately less of the metals and heavy elements than younger stars.

No adequate theory has yet been proposed to account for the production of the elements heavier than lead and up to uranium. The difficulty here arises through the decay properties and short decay times of some of these nuclei, but it remains a challenging problem for the future. The very light elements, deuterium (which is the heavy isotope of hydrogen), lithium, beryllium and

How Elements Are Produced in Stars and Distributed in Space



Jesse L. Greenstein, professor of astrophysics, working with a comparator, in which the spectra of two different stars are seen at once, presenting a comparison of the strength of lines of different elements.

boron cannot be built in the interiors of stars, as they are unstable at temperatures of only a few million degrees and will frequently tend to be broken up.

To overcome this difficulty Fowler and the Burbidges have proposed that these elements are built on the surfaces of stars, where in some cases peculiar conditions of magnetic fields, etc. exist which allow ions to be accelerated by giant betatron effects, so that they can gain enough energy to interact with the other material which is only at a few thousand degrees, and in the resulting collisions produce these elements.

To conclude, we can indicate schematically what conditions are demanded for this kind of cosmical alchemy. The diagram at the left shows how the interchange of material between stars and the interstellar medium may take place.

We believe that our galaxy was, about five billion years ago, a large turbulent whirling sphere of hydrogen gas. Within this sphere stars began to condense out of hydrogen, and the sphere began to flatten, forming the disk which we see today. Probably a number of very large stars formed, and, because they were so massive, they had a comparatively short lifetime during which a proportion of them built some of the elements by the processes described above. Then, possibly through gigantic supernova explosions, the material was blown out from them, and it formed part of the gas out of which the second generation stars were formed.

These stars may now be those which we observe to have low abundances of the metals. However, some of these stars also may have become unstable and blown off some of their material. Thus third generation stars may have formed. The majority of the stars which we can study are comparatively near to the sun. These stars are considered to have the normal "cosmical abundances" of the elements and thus may be third generation stars. However, on the basis of a theory of this sort, we would expect that the chemical composition of the stars would be related to their age and to their evolutionary tracks in time.