# THE SUN AS A PRODUCER OF ENERGY*

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### RADIANT AND GRAVITATIONAL ENERGY

THE existence of ionized layers in the earth's atmosphere is due to solar radiation, but in the *phenomena* of the ionosphere an entirely different cause plays a secondary part, namely, gravitation, exerted in the form of tidal forces, more by the moon than the sun.

The same two distinct causes provide the energy that electrical engineers develop and apply in so many ways. The sun's radiation is the chief source. Though engineering based on the direct use of the sun's heat is not yet practicable on any large scale, great use is made of past sunlight, stored up in the coal measures; and hydro-electric power comes from solar radiation of our own time, which raises water from the sea to the sky; it descends as rain, and some of this rain-water flows through turbines on its way from the highlands to the sea. A secondary source of energy is gravitational, namely, the sea tides, especially where these are magnified in narrow channels.

### SOLAR ENERGY: THE GRAVITATIONAL THEORY

Helmholtz thought that ultimately these two sources were the same—that the sun's radiation is derived from potential energy of gravity which the sun once possessed in much larger measure than it does to-day. In his view the sun was formerly a sphere of rare cool gas, far larger than now; its self-attraction caused it to contract, and as the outer layers 'fell' inwards or 'downwards' towards the centre, the gas within was compressed and its temperature rose. Thus the sun gradually became hot, from the centre outwards. When the heat had spread to the surface, the sun became luminous, and its transformed gravitational energy was poured out as radiation.

On the basis of this theory Lord Kelvin concluded that the sun could not have shone with its present brightness for more than about 20 million years, and that therefore the geological changes and the evolution of life on the earth must have been limited to this period. Impressed by his authority, some geologists accepted his estimate; others, more independent in mind and more confident in their own data, rejected it; we know now that they were right.

### THE SUBATOMIC SOURCE OF SOLAR ENERGY

These two great men, Helmholtz and Kelvin, were dealing with a real and important feature of the sun's power supply, but perforce they missed the main point, which was beyond the science of their time. The present output of solar energy is not of gravitational origin; it is produced in the central region of the sun, from subatomic energy, by a special type of combustion or chemical reaction.

The fuel is hydrogen, and of this the sun has large reserves, comprising about a third of its mass. The product of combustion is helium.

### TERRESTRIAL AND SOLAR COMBUSTION

The solar combustion has interesting analogies with the burning of coal in a furnace, but in other ways it is remarkably different. In a coal furnace one carbon atom combines in successive stages with two oxygen atoms to form a complex molecule, carbon dioxide. The reactions are essentially of the form:

$$2C + O_2 = 2CO,$$
$$2CO + O_2 = 2CO_2;$$

and in the process energy is emitted in the form of heat. The burning begins only if the coal is first heated to a suitable temperature; its combustion then maintains this temperature.

The combustion in the solar furnace likewise produces one complex particle, a helium atomic nucleus, out of four simpler particles, in this case four hydrogen atomic nuclei; and in the process energy is emitted, mainly in the form of radiation of very short wave-length, namely, $\gamma$-radiation. The process begins only when the solar gas is raised to a very high temperature and density or pressure.

Herein lies the important part played by the gravitational contraction considered by Helmholtz and Kelvin; this produces the necessary temperature and pressure, twenty million degrees centigrade and ten thousand million atmospheres, near the centre of the sun. Thereafter the 'burning' of the hydrogen nuclei can maintain the temperature and prevent further contraction for thousands of millions of years, during which the sun radiates with at least its present brightness.

One may say that the solar furnace, like some types of internal combustion engine, was ignited

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* From the earlier part of the thirty-second Kelvin Lecture to the Institution of Electrical Engineers, entitled "The Sun and the Ionosphere", delivered on May 8.

by compression. Helmholtz mistook the brightness and the radiation leakage during the initial ignition process (occupying only a few million years) for the main and much more productive process of energy generation from subatomic sources.

## ORDINARY MATTER AND NUCLEAR CRUSHED MATTER

In a coal furnace the atoms and molecules that take part in the combustion are electrically neutral systems. They consist of small positively charged nuclei, containing almost all the mass, with an outer structure of light negative electrons.

In the central solar furnace the outer structure of all atoms is broken up ; the gas therefore consists of free nuclei and free electrons. This 'crushed matter' is much more compressible than ordinary matter, and at the centre of the sun its density is about eighty-five times that of water.

Thus the combustible part of the central gas consists of hydrogen atomic *nuclei* (also called protons). These combine to form helium atomic nuclei (also called α-particles). The negative electrons present play no direct part in the combination.

## THE MAIN REACTION IN THE SOLAR FURNACE

In a coal furnace oxygen is as essential to the combustion as the coal itself, and two atoms of oxygen (or one molecule) lose their separate existence for each carbon atom 'burnt'. The oxygen has an equal right with the carbon to be considered as fuel, though because it costs nothing we may ignore this.

In the solar furnace the fuel is hydrogen nuclei or protons. But these do not combine together directly ; they are built up into helium nuclei in the course of a six-stage reaction involving a catalyst. The catalyst is a particle that undergoes a cycle of successive transformations but is left finally unchanged. At the outset of the helium-building reaction, the catalyst is an ordinary carbon nucleus ${}_6C^{12}$† ; it undergoes four successive combinations, with one proton at a time ; two of its intermediate forms are unstable, and undergo a spontaneous radioactive transformation, with the emission of a positive electron. The outcome of the fourth combination is a helium nucleus and an ordinary carbon nucleus as at first. The helium nucleus has been synthesized from the four protons, and the carbon nucleus is ready to start another such reaction cycle.

The equations of the six nuclear-chemical reactions are as follows, where I have added a + sign to the suffix as a reminder to the reader that the suffix indicates the number of elementary positive charges possessed by the particle ; also $e_+$ denotes a positive electron carrying one positive charge, and of very small mass. In each equation the sum of the suffixes on the two sides are the same, and likewise the sum of the affixes ; these equalities correspond to the conservation of charge and of mass.

2½ *million years*

$$ {}_{1+}H^1 + {}_{6+}C^{12} = {}_{7+}N_{13} + \text{gamma ray} $$

10 *minutes*

$$ {}_{7+}N^{13} = {}_{6+}C^{13} + e_+ $$

50 *thousand years*

$$ {}_{1+}H^1 + {}_{6+}C^{13} = {}_{7+}N^{14} + \text{gamma ray} $$

4 *million years*

$$ {}_{1+}H^1 + {}_{7+}N^{14} = {}_{8+}O^{15} + \text{gamma ray} $$

2 *minutes*

$$ {}_{8+}O^{15} = {}_{7+}N^{15} + e_+ $$

20 *years*

$$ {}_{1+}H^1 + {}_{7+}N^{15} = {}_{6+}C^{12} + {}_{2+}He^4 $$

Preceding the line for each reaction a time is stated ; this is an estimate of the time that elapses, under the conditions existing in the solar furnace, before the reaction occurs ; Bethe, to whom this theory and these estimates are due, states that the times may be wrong by a factor 3 either way, except the shortest two, which are based on observation in the laboratory. The three long intervals illustrate the rarity of combinations at which two nuclei combine to form a single particle with the emission of the excess energy as radiation ; this occurs only when the collision satisfies certain highly restrictive conditions. Hence the last combination, in which two particles, without radiation, result from the collision of two other particles, is far more probable than the possible alternative

$$ {}_{1+}H^1 + {}_{7+}N^{15} = {}_{8+}O^{16} + \text{gamma ray}. $$

The equations show that it takes a few million years for any one carbon nucleus, fertilized by four successive protons, to bring to birth one α-particle. If the birth-rate is high at the centre of the sun, it is because the number of carbon atoms and protons there is immensely great.

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† The chemical nature of an atomic nucleus is determined by the number of (positive) elementary charges that it carries ; for hydrogen, helium, carbon, nitrogen and oxygen nuclei these numbers (called the *atomic numbers*) are respectively 1, 2, 6, 7, 8. The nucleus is conveniently denoted by the appropriate chemical atomic symbol together with a suffix indicating the atomic number or number of positive charges (though either the number or the atomic symbol would suffice, as the atomic number uniquely determines the symbol). Thus the nuclei of hydrogen (a proton), helium (an α-particle), carbon, nitrogen and oxygen are denoted by ${}_1H$, ${}_2He$, ${}_6C$, ${}_7N$, ${}_8O$. The mass of the nucleus is not uniquely determined by the charge or atomic number ; nuclei of different masses but the same charge are called isotopes. The atomic mass may conveniently be indicated by an upper integer affix, equal (very nearly) to the chemical *atomic weight*. Thus a proton and an ordinary α-particle are denoted by ${}_1H^1$, ${}_2He^4$, and the isotopes of carbon, nitrogen and oxygen that occur in the solar central reaction are ${}_6C^{12}$, ${}_6C^{13}$ ,${}_7N^{13}$, ${}_7N^{14}$, ${}_7N^{15}$, ${}_8O^{15}$ ; of these ${}_7N^{13}$ and ${}_8O^{15}$ are unstable.

### The Energy Production

The catalytic combination of hydrogen nuclei is enormously productive of energy. Whereas the ordinary combustion of 1 lb. of coal gives heat energy equivalent to $4\frac{1}{4}$ electrical units, the 'burning' of 1 lb. of hydrogen nuclei produces radiant energy equivalent to nearly 100 million electrical units.

Energy has mass, though only 1 gram to 25 million electrical units ; hence the radiant energy produced from 1 lb. of hydrogen nuclei has a mass of 4 gm. ; the mass of the resulting helium nuclei falls short of 1 lb. by this amount—a perceptible diminution.

Helios, the sun, is a power producer on the grand scale. Its heating and lighting output is nearly half a billion billion kilowatts (more exactly, $3{\cdot}8 \times 10^{23}$ kw.), and I use billion in its English sense, to signify a million million. The corresponding loss of mass is at the rate of 4 million tons per second.

### The Outward Stream of Radiant Energy

This energy is generated in the central solar furnace mainly as gamma radiation. This struggles upwards through the immense surrounding mass of overlying gas, ever cooler and less dense the farther from the centre. The radiation is continually degraded in frequency or increased in wave-length, and finally it leaves the sun with a spectral distribution corresponding roughly to a temperature of 6,000° C. It consists of electromagnetic waves the average frequency of which is still very high, nearly a billion kilocycles per second. As it reaches the earth and other distant consumers, it is highly directional.

### Solar Surface Phenomena

In the upper layers of the sun the stream of outward flowing radiation energizes many surface phenomena on a grand scale. Of these the most evident are the sunspots and prominences. Much of the solar gas that we see raised above the surface in the form of prominences falls back again on to the sun, but some of it is expelled never to return. Thus the sun sends forth matter, as well as electromagnetic radiation, into the space around it. The matter, in the form of clouds or streams of rare gas, is a partner with the solar wave radiation in ionizing the earth's outer atmosphere.

### Energy Supply to the Earth

Of the sun's majestic outpouring of radiant and material (kinetic) energy, all but a tiny fraction is lost in the depths of interstellar space. The father Helios scatters his riches abroad with grand prodigality, and his children the planets intercept only the merest scrap of their patrimony. Our mother earth receives less than a thousand millionth of the parental output (more exactly, the fraction is $4{\cdot}5 \times 10^{-10}$). Yet her income of over 170 billion kilowatts is not small.

All this income she spends, and perhaps a little more, drawn from her own reserves. Very little of her income can she store up for the future. From one point of view, the history of the earth since she became a separate planet is largely the story of the spending of her solar income.

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# INTERACTION OF VITAMINS A AND E

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ONE of the most noteworthy properties of vitamin A is the extent to which it can accumulate in the liver. When the dietary intake is liberal, sufficient vitamin may be stored to meet ordinary requirements for a theoretical period of about a hundred years[1]. Some years ago we began experiments to find whether during a subsequent deficiency these large reserves would in practice be preserved and used up economically at a rate corresponding with physiological requirements, or whether they would be dissipated at an unduly rapid rate. In our first experiment a rapid dispersal of the vitamin A reserves was observed[2]. We emphasized, however, that this result was exceptional, since in earlier work large reserves had been found in the livers of rats after prolonged restriction to deficient diets[3].

For several years we tried to repeat, and explain, our observations on the rapid loss of vitamin A, but with unsatisfactory results. The influence of the exact nature of the basal diet was specially considered, and many minor modifications were made without affecting the rate of disappearance of the vitamin. Eventually a clue was obtained from an unexpected direction when it was found that the vitamin A reserves of rats which had been kept on a diet deficient in vitamin E were much lower than those of animals receiving equal amounts of vitamin A together with supplements of vitamin E[4].

Further unpublished experiments on this point