HIGH-DISPERSION SOLAR SPECTROGRAMS BETWEEN 15 μ AND 24 μ

In 1941 A. Adel,[1] at Flagstaff, Arizona, found a new atmospheric window by recording the solar spectrum between 15 and 24 μ. However, these observations were made under low dispersion, and the published curves show only sixteen absorption maxima (including four inflexions). To our knowledge, no other observation of the solar spectrum has been carried out in the above region.

In October, 1951, we succeeded in mapping the solar spectrum with high resolution between 15.90 and 23.73 μ; our spectrograms reveal 145 lines in this region. Toward shorter wave lengths, that is, between 14.2 and 15.9 μ, we find a complete absorption due to the 15 μ band (ν_2) of telluric CO_2. Owing to the water-vapor absorption, we have not as yet been able to detect any energy in the region beyond 23.73 μ.

Nearly all the newly observed lines have been identified. They are ascribed to the 16.24 μ band ($2\nu_2-\nu_2$) of CO_2, the 17 μ band (ν_2) of N_2O, and water vapor. New laboratory data are needed for the identification of the few remaining faint lines.

The observations have been made with the prism-grating spectrograph[2] of the University of Liége. This instrument was installed in the Jungfraujoch International Scientific Station, Switzerland, at an elevation of 11,725 feet. The spectrograph was equipped with an original echelette grating from the University of Michigan, having 1200 lines per inch (dimensions of the ruled surface: 7×9 inches). As receiver, we used a Perkin-Elmer thermocouple, which was connected to a Leeds and Northrup Speedomax recorder, through a 13-cycle Perkin-Elmer electronic amplifier.

We are indebted to the Fonds National Belge de la Recherches Scientifique, the Royal Observatory of Belgium, and the University of Liége for their support of this work.

M. Migeotte
L. Neven

Jungfraujoch
October 20, 1951

NUCLEAR REACTIONS IN STARS WITHOUT HYDROGEN*

The more luminous main-sequence stars (O and B) exhaust their hydrogen supply in times of the order of magnitude of 10^9 years or less, the bulk of the hydrogen being converted into helium by means of the carbon-nitrogen cycle. When the energy supply of the carbon-nitrogen cycle has been exhausted, the star undergoes gravitational contraction, and its temperature increases. Various nuclear processes[1, 2, 3] have been suggested for such a contracting star, all of which require temperatures of well over $10^{9\circ}$ K. The main aim of this note is to point out that there is one nuclear process which takes place at a much lower temperature of about $2\times10^{8\circ}$ K, namely, the conversion of three helium nuclei into one carbon nucleus.

We take as an example a main-sequence star of mass $5M_\odot$ (B8 star), central density

[1] *Ap. J.*, **96**, 239, 1942.

[2] M. Migeotte, *Mém. Soc. R. Sci. Liége*, 1st ser., Fasc. 3, Vol. **1**, 1945.

* This work was carried out during the summer of 1951 at the Kellogg Radiation Laboratory, California Institute of Technology, Pasadena. The author is indebted to several colleagues at the California Institute of Technology and at the Mount Wilson and Palomar Observatories for valuable discussions.

[1] F. Hoyle, *M.N.*, **106**, 343, 1946.

[2] G. Gamow and M. Schoenberg, *Phys. Rev.*, **59**, 539, 1941.

[3] L. Borst, *Phys. Rev.*, **78**, 807, 1950.

$\rho = 25$ gm/cm^3, and central temperature $T = 2 \times 10^{7\circ}$ K. The average energy radiated by the star, $\bar{\epsilon}$, is about 60 erg/gm sec, and most of the hydrogen is exhausted in about 10^9 years. We assume that in the ensuing gravitational contraction the central temperature and density are given by

$$T \propto R^{-1}\,, \qquad \rho \propto R^{-3}\,, \tag{1}$$

where R is the radius of the star. Gravitational energy is the only source of energy during the contraction until temperatures over $10^{8\circ}$ K are reached in a few million years. At these temperatures the following nuclear reaction sets in:

$$\begin{aligned} He^4 + He^4 + 95 \text{ kev} &\rightarrow Be^8 + \gamma\,, \\ He^4 + Be^8 &\rightarrow C^{12} + \gamma + 7.4 \text{ mev}\,. \end{aligned} \tag{2}$$

The nucleus Be^8 is unstable to disintegration into two He^4 nuclei. But, since an energy of only (95 ± 5) kev, comparable with thermal energies at temperatures over $10^{8\circ}$ K, is required for its formation, a fraction of about 1 in 10^{10} of the material of the star is kept in the form of Be^8 in a state of dynamic equilibrium. The Be^8 present then easily absorbs a helium nucleus. Once carbon has been produced, the following reactions also become possible

$$C^{12} + He^4 \rightarrow O^{16} + \gamma + 7.1 \text{ mev}\,, \tag{3a}$$

$$O^{16} + He^4 \rightarrow Ne^{20} + \gamma + 4.7 \text{ mev}\,, \tag{3b}$$

and so on. Owing to the increasing Coulomb barrier, the reaction rates decrease with increasing atomic number. Assuming the absence of γ-ray resonances, the rates for reactions (2) and (3*b*) are of the same order of magnitude. Hence the helium is probably converted mainly into C^{12}, O^{16}, and Ne^{20} and into decreasing amounts of Mg^{24}, Si^{28}, S^{32}, A^{36}, and Ca^{40}.

Energies of 3-4 mev per helium nucleus are produced in these reactions (about one-seventh the production in the carbon-nitrogen cycle). At temperatures T in the neighborhood of $2 \times 10^{8\circ}$ K, the rate of energy production ϵ is given by

$$\epsilon = 10^3 \left(\frac{\rho}{2.5 \times 10^4}\right)^2 \left(\frac{T}{2 \times 10^{8\circ}\text{K}}\right)^{18} X_\alpha^3 \text{ erg/gm sec}\,, \tag{4}$$

where ρ is the density in gm/cm^3 and X_α is the concentration by weight of helium. No detailed calculations have as yet been carried out with specific stellar models, but a temperature of slightly more than $2 \times 10^{8\circ}$ K should be sufficient for the energy generation (4) to supply the radiative-energy loss. In deriving equation (4), the nuclear γ-ray width for the formation of C^{12} (but *not* the one for Be^8) is required. This width has not yet been measured, and the position of resonance levels is not yet known accurately enough, and an estimate of 0.1 e.v. was used for this width. Hence the correct production rate could be smaller than equation (4) by a factor of as much as 10, or larger than equation (4) by as much as 1000. However, even a factor of 1000 in the production rate alters the temperature necessary by a factor of only 1.33. If we assume an average radiative-energy loss of about 200 erg/gm sec, the energy content of reactions (2) and (3) is sufficient to maintain the star at an almost constant temperature and radius (central density ρ about 2.5×10^4 gm/cm^3) for about 5×10^7 years, after which time the bulk of the helium will have been converted into carbon and heavier nuclei.

We are thus led to the conclusion that *a few per cent of all visible stars of mass $5M_\odot$ or larger are converting helium into heavier nuclei, the central temperature being about ten times larger (and radius ten times smaller) than that of a main-sequence star of the same mass*. It is hoped that some connection will be found between stars undergoing this process, on the one hand, and carbon-rich and high-temperature stars (Wolf-Rayet, nuclei of planetary nebulae), on the other (and possibly even with some of the variable stars and novae).

The fate of stars which have exhausted their helium supply and consist mainly of carbon, oxygen, and neon is much more controversial, but some tentative qualitative conclusions can be drawn about the various competing nuclear reactions. The star again contracts gravitationally until temperatures of about $10^{9°}$ K are reached. At these temperatures collisions between two C^{12} nuclei, giving Mg^{24} or $(Na^{23} + H^1)$, become possible and at slightly higher temperatures collisions involving O^{16} and Ne^{20}. At temperatures of $(2 \text{ to } 4) \times 10^{9°}$ K the dissociation of the lighter nuclei into helium nuclei and into protons becomes important. These helium nuclei and protons can be absorbed by heavier nuclei, with the result that a significant fraction of the nuclei in the star might be converted into a variety of different nuclei of atomic weight A up to about 40 or 60. The relative concentrations of the various nuclear species might be expected to be similar to that obtained on Hoyle's[1] theory of thermodynamic equilibrium. At $(1 \text{ to } 4) \times 10^{9°}$ K, however, the Urca processes of Gamow and Schoenberg[2] become important, which extract energy from the star in the form of escaping neutrinos. This energy loss results in a very rapid contraction of the star without any increase in temperature, as soon as the energy supply from the conversion into the very stable nuclei (A about 40–60) is exhausted. This contraction continues (unless the star becomes unstable because of its rotational momentum) until densities of more than 10^{10} gm/cm^3 are reached. The electron gas is then highly degenerate, and fairly large concentrations of beta-active nuclei are built up because of the high kinetic energies of the degenerate electron gas. More detailed calculations will be necessary to determine whether enough time is available during this collapse to build up the very heavy nuclei (up to uranium), as was suggested by Hoyle.[1] If the star becomes unstable during the collapse and becomes a supernova, one would expect the various beta-active nuclei to be expelled and to decay in the envelope of the supernova. These considerations lead to difficulties for Borst's[3] hypothesis that the energy generation in envelopes of supernovae of type I is due, to a large extent, to the beta decay of one *single* nucleus, Be^7, obtained from the reaction $He^4 + He^4 \rightarrow Be^7 + n$. It may, however, be possible that this reaction predominates over the others discussed in this note, if in a supernova of type I convection sets in suddenly (with velocities comparable to those of free fall), so that He^4 from the cooler outer layers of the star is *suddenly* brought into the central regions at a temperature of about $4 \times 10^{9°}$ K. It should be emphasized again that the remarks in *this* paragraph are quite tentative and speculative.

A fuller account of the calculations on the various processes discussed in this note will be given elsewhere.

E. E. SALPETER

LABORATORY OF NUCLEAR STUDIES
CORNELL UNIVERSITY
October 2, 1951

A NOTE ON ENERGY GENERATION IN RED DWARF STARS

Recent work by I. Epstein,[1] J. B. Oke,[2] and others[3] has indicated that the proton-proton reaction may be the most important source of energy generation in the cooler stars of the main sequence and even in the sun.

We have attempted to compute a model for the red dwarf star Krueger 60A, taking into account the energy generation throughout the layers where it may occur, on the assumption that the proton-proton reaction alone is responsible for the energy production. We have adopted for the mass, luminosity, and radius of the star the following data: $\log M = -0.60$, $\log L = -1.77$, $\log R = -0.29$.

[1] *Ap. J.*, **112**, 207, 1950.

[2] *J.R.A.S. Canada*, **44**, 135, 1950.

[3] See, e.g., L. H. Aller, *Ap. J.*, **111**, 173, 1950.