planar K-shaped tetrad of pyriform lobes. The formation of two more buds on the opposite side produced a symmetrical planar hexad; double-budding next occurred in a plane at right-angles to that of the hexad giving octads and then decads. Beyond the decad stage the lobes are so closely packed that we are unable to follow the hypothetical developmental sequence in detail; but it seems clear that they passed through this multi-lobed stage, measuring about 4 μ in diameter, to a final stage in which the clear outlines of the individual lobes are almost obscured and the objects are roughly spherical, about 4.2 μ in diameter, with a raspberry-like surface. The occasional detachment of single viable pyriform lobes or more complex aggregates could have completed the cycle. It appears that less regular developmental sequences, often involving the retarded "maturation" of one or more buds, must have been common.

The proportion of yellow objects in pockets of the Y series which cannot easily be interpreted as stages in the described developmental sequence is small. However, some of the yellow material occurs as minute, roughly equidimensional, angular granules scattered singly or in groups throughout the rock sections. Their size varies considerably, but is generally up to about 0.6 μ. We assume at present that the granules do not belong (in the developmental sense) to the Y series, because of their irregular shape and size, and the fact that they are more common in the red than in the yellow pockets, but we have no suggestions to make about their origin or significance.

We are also unable to say much about the relatively rare objects of the M series (Fig. 1, *w*, *x*, and *y*) which are up to about 8 μ across. They consist of a yellow core often lacking the symmetrical lobulate structure of advanced stages of the Y series, partially surrounded, and sometimes more or less enclosed, by typical objects of the R series. But they are not the invariable consequence of the mixing of objects of the R and Y series, because members of those two series are sometimes found to be freely intermingled at the junctions of red and yellow pockets without the formation of any M objects.

No carbon has been detected in the quartzite, and we have no direct evidence for supposing the colored objects to be of biological origin; nor can we prove that the orders in which we have described the various R and Y forms actually correspond to temporally-successive stages of development. Indeed, some of the forms occur rather less frequently than we would have expected if our proposed sequences were completely correct. On the other hand, we are unable to conceive of any inorganic processes which would give rise to series of minute, rounded, and seemingly noncrystalline objects of such constant dimensions, assembled into such markedly lifelike patterns as these just described. It might be argued, however, that the most complex objects in the R and Y series are really the remains of relatively resistant "fruiting bodies" composed of masses of the "spores" of higher organisms whose vegetative structures have completely disappeared; and that we are merely observing stages in the disaggregation of the spore masses into their constituent units. But such an interpretation would not account satisfactorily for the bacilliform and figure-eight objects in the R series, or for the partially-formed buds in the Y series. We therefore feel that although our reconstructions of the "life-cycles" may be confused or incomplete, they do at least have the arrow of time pointing in the right direction.

It seems that the microorganisms, if such they were, could have been either iron-oxidizers during life, or that the oxides were formed as the result of secondary changes after death. The occurrence of objects of the R series which have been distorted by entry into exceptionally narrow veinlets (Fig. 1*g*) or of the Y series which have been squashed flat between adjacent quartz grains (Fig. 1*v*) suggests that they were plastic at some stage.

The most intractable aspect of the problem is the assessment of the age of the objects. They cannot be younger than the interstitial cement in which they are imbedded, but the date of the silicification producing that cement is at present unknown; it might have occurred at any time later than the Archaeozoic. If the cement is in fact opal, it seems probable that it must have been formed more recently than the Precambrian and fairly near to the surface rather than at great depth. But the objects could have been present in the rock long before the period of silicification. Thus, at present it can only be said that the objects of the R and Y series are apparently fossilized microorganisms of two new species and that, if they are contemporaneous with the sediments in which they occur, they are possibly at least 700 million years older than the oldest structurally preserved organisms previously described (*3*).

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9 December 1963

Solar Neutrons and the Earth's Radiation Belts

Abstract. *The intensity and spectrum of solar neutrons in the vicinity of the earth are calculated on the assumption that the low-energy protons recently detected in balloon and satellite flights are products of solar neutron decay. The solar-neutron flux thus obtained exceeds the global average cosmic-ray neutron leakage above 10 Mev, indicating that it may be an important source of both the inner and outer radiation belts. Neutron measurements in the atmosphere are reviewed and several features of the data are found to be consistent with the estimated solar neutron spectrum.*

In a recent communication Simpson suggested (*1*) that the continuous flux of protons below 200 Mev observed in balloons in the upper atmosphere (*2*) and on the earth satellite Explorer XII (*3*) may be the decay product of neutrons emitted by the sun. We consider here the energy spectrum and intensity of the solar-neutron flux required to produce the observed low-energy protons. If Simpson's hypothesis is correct, the solar neutron flux should be detectable over equatorial regions of the earth and should constitute an important source of the inner and outer radiation belts.

The low-energy proton data obtained in 1960 and 1961 are shown in Fig. 1, together with the estimated galactic cosmic-ray spectra above 350 Mev at the time of the measurements. No major solar flares occurred for at least a week prior to the detection of the low-energy protons. Moreover, the low-energy spectrum remained constant over periods of several days, indicating that the protons were not the residue from previous major flares. Nevertheless, the flux below 200 Mev decreased with the decrease in solar activity between 1960 and 1961, indicating that the protons were of solar origin. The galactic cosmic ray flux, in contrast, is negatively correlated with solar activity owing to modulation by the interplanetary field. From these observations, Meyer and Vogt (*2*) concluded that the proton flux below 200 Mev is emitted by the sun either continuously or in association with frequent small flares. Simpson (*1*), noting the difficulty of freeing low-energy charged particles from solar magnetic fields, proposed the alternative hypothesis that neutrons produced in the solar atmosphere by interaction of accelerated, trapped protons and alpha particles may escape to decay in space. The principal reactions involved presumably are $He^4(p,d)He^3$, followed by deuteron stripping, and $He^4(p,pn)He^3$ (*4*).

In order to determine the solar contribution to the low-energy proton flux, the galactic cosmic-ray flux in Fig. 1 was extrapolated to lower energies and subtracted from the data points between 80 and 300 Mev. In the absence of data between 10 and 80 Mev, the flux in this region was assumed to be constant at the average value. The resultant spectra of low-energy protons for September 1960 and August 1961 are shown in Fig. 2. Also shown in Fig. 2 is the expected differential flux of solar neutrons reaching the orbit of the earth in association with the low energy protons, if it is assumed that all of the protons arise from neutron decay. The neutron intensity at each energy is equal to the proton intensity at that energy multiplied by the expected ratio of solar neutrons to decay protons at the earth's orbit, calculated from the probability that a neutron of

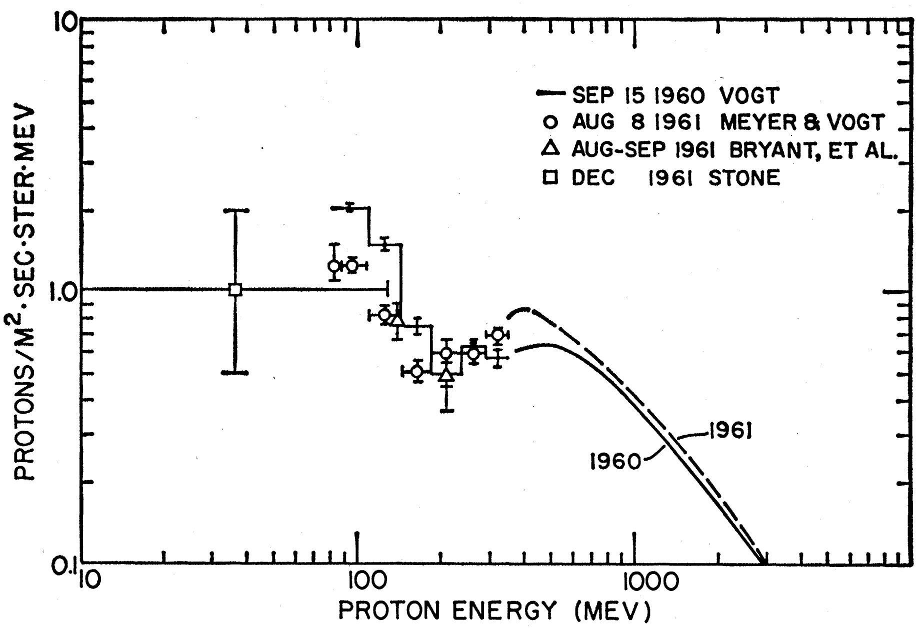

Fig. 1. The low energy solar proton data obtained in 1960 and 1961, together with the estimated galactic cosmic ray spectra above 350 Mev at the time of the measurements (*2*, *3*).

the specified energy will decay to a proton during the sun-earth transit time. Integration of the neutron spectra over energy yields total fluxes of approximately 0.07 neutron $cm^{-2}sec^{-1}$ above 10 Mev for 1960 and 0.03 neutron $cm^{-2}sec^{-1}$ above 10 Mev for 1961, with about 90 percent of the total flux above 50 Mev in both years.

A comparison may be made between the estimated solar neutron fluxes shown in Fig. 2 and the neutron flux produced by interaction of galactic cosmic rays with the earth's atmosphere. From Lingenfelter's calculations of the equilibrium cosmic-ray neutron flux (*5*), the global average neutron leakage at the top of the atmosphere is about 0.025 n $cm^{-2}sec^{-1}$ above 10 Mev at solar minimum and 0.018 n $cm^{-2}sec^{-1}$ above 10 Mev at solar maximum. Hence, in the energy range above 10 Mev, the estimated solar neutron fluxes in the vicinity of the earth are two to three times larger than the global average cosmic-ray neutron leakage flux. Moreover, the solar neutron fluxes above 50 Mev at the top of the atmosphere are 60 to 90 times larger than the cosmic-ray neutron leakage above that energy. It should be noted that the relative intensity of the solar and cosmic-ray neutrons shows strong diurnal and latitude variations. The former decreases with increasing distance from the subsolar point whereas the latter increases with increasing geomagnetic latitude. The ratio of solar to comic-ray neutrons is largest at the top of the atmosphere at noon over the equator; here the estimated solar neutron flux during 1960 exceeds the cosmic-ray neutron leakage by an order of magnitude for the energy range above 10 Mev and by two orders of magnitude for the energy range above 50 Mev. In fact, the solar neutron flux at mid-day at the equator, during 1960–61, would overwhelm the cosmic-ray neutron flux above 50 Mev at all depths down to at least the Pfotzer maximum corresponding to a pressure of 100 g/cm^2 of residual atmosphere. A diurnal variation of the neutron flux at the equator thus should be detectable at all altitudes above the Pfotzer maximum with counting equipment selectively sensitive to high-energy neutrons.

The search for solar neutrons has previously been conducted with detectors sensitive in the thermal or intermediate energy range, where the estimated solar neutron fluxes may be small compared to the cosmic-ray neutron flux. A diurnal effect consisting of a peak just before sunset nevertheless was recorded by thermal detectors on three balloon flights, two in 1958 (*6*) during the maximum of the last solar cycle and one near the maximum of the previous solar cycle (*7*). No such peak was found in subsequent flights in 1963 during solar minimum (*8*). As suggested by Haymes (*6*), these peaks may represent low-energy secondary neutrons produced in cascade processes initiated by solar neutrons penetrating the rapid-

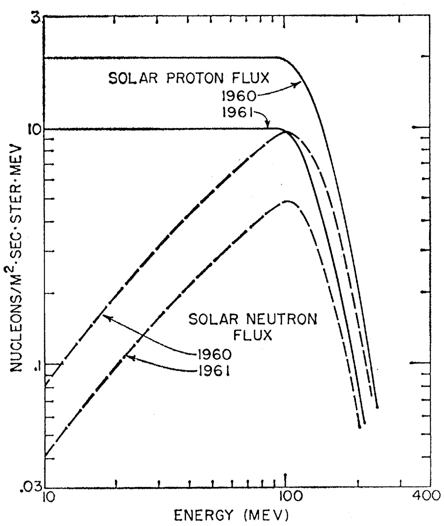

Fig. 2. The solar proton spectra for 1960 and 1961, and the accompanying solar neutron spectra at 1 A. U., if it is assumed that the protons result from neutron decay.

ly increasing thickness of atmosphere between the detector and the sun just before sunset. The optical path length to the sun at the time of the peak was roughly 120 g/cm^2. A solar neutron flux of the magnitude and spectral shape estimated for 1960 could account for a thermal neutron peak of the observed magnitude at the latitude, altitude, and time of Haymes' observations.

The only two neutron measurements made until now with equipment selectively sensitive in the energy range above 50 Mev (*9, 10*) are at atmospheric depths corresponding to pressures of 200 or more grams per square centimeter. Since the ratio of the estimated solar neutron flux to the equilibrium cosmic-ray neutron flux decreases rapidly below the Pfotzer maximum, these measurements do not provide a positive test of the solar-neutron hypothesis. The two measurements do, however, differ by a factor of seven, with the lower value obtained near solar minimum (*10*) and the higher value at solar maximum (*9*). Though this may result from instrumental difficulties, such a correlation between the high-energy neutron flux and solar activity is also suggestive of solar neutrons.

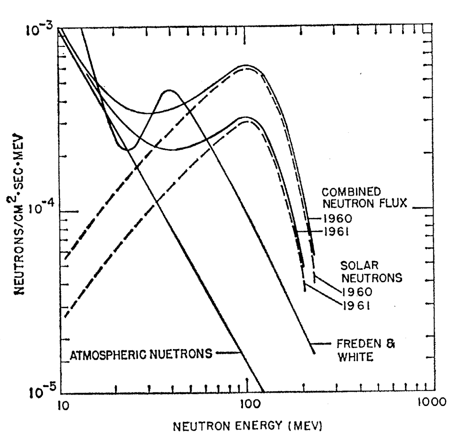

Fig. 3. "Combined neutron flux," for 1960 and 1961, resulting from the combined flux of atmospheric leakage neutrons and solar neutrons. For comparison the curve "Freden and White" is the neutron spectrum calculated by these authors to produce the observed spectrum of trapped protons in the inner radiation belt in magnetic shells with L values of about 1.3.

Next, we consider the possible importance of such a solar neutron flux as a source of the earth's radiation belts. The trapped protons above 10 Mev in the inner radiation belt have previously been attributed to decay of cosmic-ray leakage neutrons in the vicinity of the earth. Since the estimated solar neutron flux at the top of the atmosphere for 1960 and 1961 is two to three times greater than the global average cosmic-ray neutron leakage above 10 Mev, it would also constitute an important source of the inner radiation belt. Furthermore, the addition of a solar neutron component to the cosmic-ray neutron leakage source could account for the second peak in the spectrum of the inner belt protons observed by Freden and White (*11*). The curve marked "Freden and White" in Fig. 3 is the neutron spectrum calculated by these workers to produce the observed spectrum of the inner belt protons trapped in magnetic shells at an L value of about 1.3. In contrast to the structure in this curve, the typical spectrum of cosmic-ray leakage neutrons decreases monotonically with increasing energy (*12*).

The estimated solar neutron spectra for 1960 and 1961 are also shown in Fig. 3. Addition of the cosmic-ray neutron leakage and the solar neutron spectra yields the curves marked "combined neutron flux." Both the position of the trough and the height of the second peak of these curves are strongly dependent on the low-energy proton spectrum below 80 Mev; the region in which experimental data are lacking. Nevertheless, it is apparent that far better agreement with the Freden and White spectrum could be obtained both in total intensity above 10 Mev and in spectral shape if a solar neutron component were added to the cosmic-ray leakage.

Finally, we consider the average density of neutron decay in the earth's magnetosphere. Owing principally to geometric factors, the high energy cosmic-ray neutron leakage flux falls off rapidly with increasing distance from the top of the atmosphere. The solar neutron flux, in contrast, is essentially constant throughout the magnetosphere. Hence the ratio of solar neutrons to cosmic-ray leakage neutrons increases roughly as R^2, where R is in units of earth radii. As a consequence, the average decay density in the magnetosphere of cosmic-ray leakage neutrons above 50 Mev is more than three orders of magnitude smaller than the estimated decay density of solar neutrons of the same energy. These figures apply to 1961, a year of approximately average solar activity. Thus, if decay of solar neutrons is indeed the source of the low energy protons observed over the earth, it must also be an important source of the trapped particles in the outer as well as the inner radiation belt.

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4 March 1964