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CHARLES H. SCHAUER
VICE PRESIDENT AND SECRETARY

March 8, 1966
Rec'd 14/3/66

Dear Grote:

I can't resist cluttering the mails every once in a while when I encounter something that may have a remote bearing on one or more of your interests; hence the enclosure.

Aside from that, this may reach you around about the time the Hinkleys arrive at Wrest Point. Please give them my good wishes. In addition to that, in case I don't catch up with Bill at a later point in his itinerary, possibly you will relay a warning for him to beware of the University of Hawaii. I have just seen a note indicating they're going into a Ph.D. program in Astronomy, with the Department of Physics adding "and Astronomy" to its name. The same note indicated the existence of a couple of University-operated allegedly astronomy stations on Maui, which name may be familiar to you.

I'll be looking forward to Bill's return with firsthand information on how your operations stand and what the prospects are. I believe I have indicated before that as usual you have titillated my curiosity without being overly informative on a subject. Cosmic ray astronomy is now added to cosmology in this category.

Best wishes,

Charles H. Schauer

CHS:JE
Enclosure

P.S. JFI reprints just arrived. Mebbe reading one will enlighten me. (25 copies are being sent to you today)
arrived 27/4/66 with 26¢ postage

From

C. H. SCHAUER

3/9/66
(9/3/66)

Hi, Grote - here I go again. You haven't complained about my loading of the mails, and until you do I'm likely to continue to send you random and possibly relevant things that catch my eye.

Best -
Hap

Rec'd 14/3/66

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Response of a Standard IGY Neutron Monitor

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Abstract. On the basis of experimental results on neutron production by protons and muons, the total counting rate and the detected multiplicity spectrum normally recorded by a standard IGY neutron monitor are analyzed in terms of the components of the cosmic radiation at sea level. It is shown that approximately 93% of the detected neutrons are caused by neutron and proton interactions and that a definite relation exists between the detected multiplicity spectrum and the energy spectrum of nucleons at sea level. It is expected that time variations in the rates of the detected multiplicities will reflect the behavior of the primary energy spectrum of the cosmic radiation at energies up to the order of 200 Gev, and that this will be useful in the study of the various time-dependent phenomena of the cosmic radiation.

INTRODUCTION

The multiple production of evaporation neutrons produced by the cosmic radiation in a standard IGY neutron monitor [*Simpson*, 1957] has been investigated by operating such a monitor in coincidence with a magnetic spectrograph. The interactions of individual protons and muons have been identified, and the neutron production caused by these particles has been studied over the energy range 0.33 to 150 Gev. The results of these experiments have been discussed in two previous publications [*Hughes et al.*, 1964; *Meyer et al.*, 1964]. This work will be referred to as experiments 1 and 2, respectively.

On the basis of the results obtained in experiments 1 and 2 an attempt is made in the present paper to account for the total counting rate and the detected multiplicity spectrum normally recorded by an IGY neutron monitor in terms of the various components of the cosmic radiation at sea level. The experimental results concerning multiple neutron production by cosmic-ray protons and muons which are used in the following sections of this paper are fully described in the references to experiments 1 and 2.

Analysis of the Response of the Monitor

(*a*) *Introduction.* Curve (*a*) of Figure 1 shows the average daily rates at which the various neutron multiplicities are detected by an IGY monitor operated at sea level at Leeds, England (vertical threshold rigidity 2.1 Gev/*c*). Neutron multiplicity is defined as the number of neutrons detected within a 700-μsec interval after the detection of the first neutron and includes the first neutron to be detected. The spectrum in Figure 1 refers only to neutrons detected as a result of interactions in the lead of the monitor, since the contribution of neutrons produced in the surrounding paraffin wax has been removed. This correction, determined empirically, amounts to approximately 30% of the detected multiplicities of one neutron, 0.5% of the multiplicities of two neutrons, and is negligible for the higher multiplicities.

The rate N_i at which neutrons are detected by the monitor in response to a particular component of the cosmic radiation is given by the product of the intensity I_i of that component, the probability P_i that it will interact in the monitor, the average number of neutrons $\bar{\nu}_i$ produced in each interaction, and the efficiency ϵ with which neutrons are detected. Thus

$$N_i = I_i \cdot P_i \cdot \bar{\nu}_i \cdot \epsilon \cdot A \qquad (1)$$

where A is the horizontal surface area of the lead in the monitor.

The cosmic radiation is considered in terms of its neutron, proton, pion, muon, and extensive air shower components. For each component the quantities necessary to evaluate the corresponding rate N_i are taken from the results of experiments 1 and 2 and from the results of

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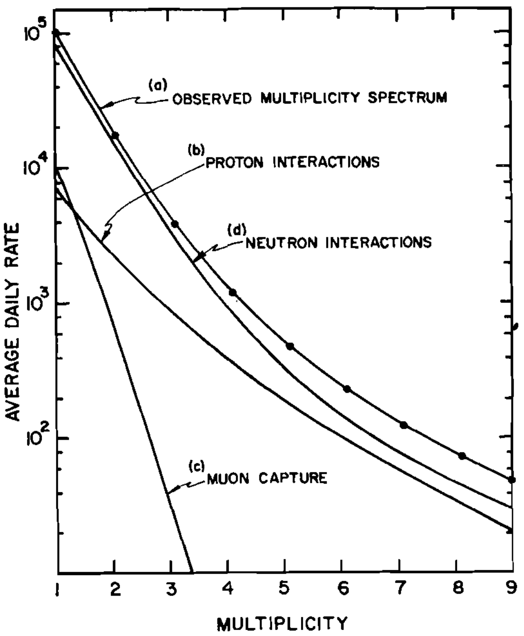

Fig. 1. The contributions to the multiplicity spectrum observed in the standard monitor due to neutron, proton, and muon interactions.

experiments on the intensities of the various components.

(*b*) *The proton contribution.* Figure 2 shows the observed distribution of neutron multiplicities caused by the interactions of protons in the lead of the monitor (experiment 1). This spectrum represents the multiplicity distribution due to protons with energies greater than about 180 Mev, the minimum energy required for a proton to penetrate the paraffin wax shield surrounding the monitor. The average number of evaporation neutrons produced in the monitor by proton interactions has been deduced from this spectrum; the result is 18.9 ± 1.7 [*Hughes,* 1961], obtained as follows. The observed multiplicity distribution is curved on a semilogarithmic scale and therefore indicates that the corresponding neutron production spectrum is not a simple exponential [*Geiger,* 1956]. The observed spectrum can, however, be reproduced if the production spectrum is resolved into two-component exponential spectrums with different average multiplicities. The solid curve in Figure 2 shows the best fit to the observed spectrum obtained in this way and corresponds to an average produced number of neutrons of 18.9 ± 1.7.

The intensity of the proton component of the cosmic radiation at sea level has been estimated using a number of experimental determinations of the differential proton energy spectrum. *Meshikovski et al.* [1958] have measured this spectrum from 60 to 390 Mev, *Ogilvie* [1955] from 200 to 600 Mev, *Mylroi and Wilson* [1951] from 180 Mev to 11.1 Gev, and *Brooke and Wolfendale* [1964] from 1.2 to 150 Gev. Combining these results, the omnidirectional intensity of protons incident on the monitor with energies greater than 180 Mev is found to be $(1.51 \pm 0.03) \times 10^{-4}$ cm^{-2} sec^{-1}. The effective thickness of the lead target in the monitor was 16.6 cm, slightly larger than the average thickness, 13.3 cm, as a consequence of the angular distribution of the incident protons, and the interaction cross section was taken to be the geometrical value $(15.3 \pm 0.8) \times 10^{-25}$ cm^2. For protons with energies in the range 180 to 610 Mev the effective thickness of the target was appropriately decreased, since ionization

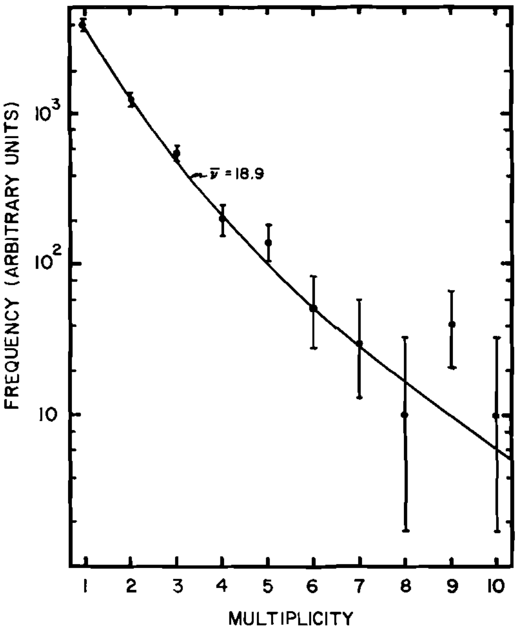

Fig. 2. The observed multiplicity spectrum due to interactions of the proton component of the cosmic radiation. The solid line shows the multiplicity spectrum expected according to a two-component production spectrum, which was constructed in order to determine the average number of neutrons produced in the monitor by proton interactions.

loss in the lead prevents such protons from penetrating the full thickness of lead.

Substituting the above quantities into equation 1, together with the appropriate value of the detection efficiency $\epsilon = 0.03$, gives the number of recorded neutrons per day resulting from proton interactions as $(1.89 \pm 0.3) \times 10^4$. These neutrons will be distributed according to the multiplicity spectrum of Figure 2, and will give a contribution to the daily spectrum shown as curve (*b*) in Figure 1.

(*c*) *The muon contribution:* 1. Muon capture. Negatively charged muons that have enough energy to penetrate the initial 11 inches of paraffin wax and are then brought to rest in the lead have a very high probability of being captured by a lead nucleus, thereby producing an average number of neutrons of 2.17 ± 0.2 [*Conforto and Sard,* 1952]. The intensity of muons between the energy limits required to penetrate the wax and to stop in the lead (136 Mev $< E_\mu <$ 480 Mev) has been derived from the muon energy spectrums measured by *Caro et al.* [1950] and F. E. Taylor (private communication, 1961) and found to be $(6.50 \pm 0.70) \times 10^{-4}$ sec^{-1} cm^{-2}.

The average number of neutrons detected by the monitor from this source is therefore $(1.15 \pm 0.2) \times 10^4$ per day distributed according to the spectrum shown as curve (*c*) in Figure 1.

2. Muon interactions in flight. Both positively and negatively charged muons can give rise to evaporation neutrons, via the photons generated by their energetic knock-on electrons and through their electromagnetic interactions with the nucleus. The results of experiment 2 have shown that the product of the cross section and the average neutron multiplicity for the combined effect of these two interactions, averaged over the energy spectrum of the muons at sea level, is about 20.0×10^{-29} cm^2 per nucleon. Using the observed muon energy spectrums of F. Ashton (private communication, 1961) and Taylor, the total intensity of muons capable of interacting in this way is found to be 11.6×10^{-3} sec^{-1} cm^{-2}, corresponding to a counting rate of 8.0×10^2 neutrons per day for the standard monitor. This contribution is not included in Figure 1 in view of its insignificance.

(*d*) *The pion contribution.* The analysis of neutron production by negatively charged particles in experiment 1 suggests that the omnidirectional intensity of pions at sea level is of the order of 1.5×10^{-6} sec^{-1} cm^{-2} ster^{-1}, or approximately 1% of the proton intensity. On the assumption that pions interact in lead with the same cross section as protons, and produce the same number of neutrons, the monitor will normally detect about 250 neutrons per day from this source, again a negligible contribution.

(*e*) *The contribution from extensive air showers.* The average neutron multiplicity produced by showers of median densities ranging from 5 to 50 particles per square meter has been measured by operating a standard monitor in coincidence with a shower selecting device [*Fieldhouse et al.,* 1962]. The results show that the average detected multiplicity remains substantially constant at a value of about 2.2 neutrons over this range of densities and that neutrons are detected in coincidence with about 10% of the showers striking the monitor. From these figures it is estimated that the monitor normally counts about 120 neutrons per day in response to extensive air showers.

(*f*) *The neutron contribution.* The average daily counting rate and the observed multiplicity spectrum of the monitor are given in Table 1, together with the contributions expected from the various components of the cosmic radiation previously discussed. It is seen that these components can account for only about 20% of the total counting rate, and it is inferred that the remainder is due to the interactions of fast neutrons. Accepting this inference, Table 1 shows that in a standard IGY monitor $81.3 \pm 2.4\%$ of the detected neutrons can be attributed to neutron interactions, $11.2 \pm 1.1\%$ to proton interactions, $6.8 \pm 1.2\%$ to captured muons, and less than 1% to the combined effects of muons in flight, pions, and the various components of extensive air showers.

Figure 1 shows how the observed multiplicity spectrum is built up from the contributions due to neutron, proton, and muon capture interactions, and reveals two significant properties of this spectrum. First, as the detected multiplicity increases, the neutron and proton contributions to the observed rates become more nearly equal, suggesting that the intensities of neutrons and protons in the atmosphere are

TABLE 1. Contributions of the Various Components of the Cosmic Radiation to the Counting Rate and Multiplicity Spectrum Detected by the Monitor

	No. of Neutrons Detected per Day	Percentage Contribution	Multiplicity Spectrum								
			1	2	3	4	5	6	7	8	9
Total cosmic radiation	169,064	100.0	104,540	20,064	4370	1305	520	245	133	78	49
Protons	18,940	11.2 ± 1.1	7,516	2,410	905	381	190	97	55	33	20
Muons captured	11,500	6.8 ± 1.2	10,756	709	32						
Muons in flight	803	0.5	499	106	23	4	1				
Pions	250	0.1	85	30	13	5	3	2	1	1	
Showers	126	0.05	36	13	6	3	2	1	1		
Neutrons	137,445	81.3 ± 2.4	85,648	16,796	3391	912	324	145	76	44	29

approaching common values at high energies. In fact, to within the error with which the spectrum due to proton interactions is determined from Figure 2, the component spectrums due to neutron and proton interactions become identical as the multiplicity increases. Second, it follows that the large fraction of the counting rate caused by neutrons is caused mainly by relatively low-energy neutrons. These features give the first indication that the shape of the observed multiplicity spectrum reflects the properties of the nucleon energy spectrum in the atmosphere and that the observed rates of the large multiplicities do not merely correspond to the accidental detection of a large fraction of the number of neutrons produced in low-energy interactions.

The average number of neutrons produced in the monitor by neutron interactions, deduced from curve (*d*) of Figure 1, is 11.7 ± 0.6, which is smaller than the value 18.9 for proton interactions because of the excess of low-energy neutrons in the atmosphere. Such a difference is qualitatively consistent with observed nucleon-nucleus reactions in emulsions; for example, *Brown et al.* [1949] have shown that stars with only a few dense tracks are mostly produced by neutral particles, and the frequencies of stars with charged and neutral primaries become equal only at very high energies.

For comparison the average number of neutrons produced in the monitor by nucleon interactions is 12.9 ± 0.6. This value, very similar to that for neutron interactions alone, is deduced from the total spectrum in Figure 1, corrected for the contribution from captured muons. The similarity demonstrates again the large part played by neutron interactions in the over-all response of the monitor.

(*g*) *The intensity of the nucleonic component of the cosmic radiation.* The fraction of the observed multiplicity spectrum now known to arise from nucleon interactions in the monitor can be used to estimate the absolute intensity of the nucleonic component of the cosmic radiation at sea level. Using the rate of detected neutrons from nucleon interactions given in Table 1, and taking the average number of neutrons produced to be 12.9 ± 0.6, equation 1 gives a value of $(10.0 \pm 0.7) \times 10^{-4}$ sec^{-1} cm^{-2} for the intensity of the nucleonic component. This value refers to the neutrons and protons that have sufficient energy to penetrate the 11 inches of paraffin wax moderator surrounding the monitor.

From similar types of experiments *Geiger* [1956] obtained values of $(33 \pm 11) \times 10^{-4}$ and $(24 \pm 8) \times 10^{-4}$ sec^{-1} cm^{-2} for the intensity of the nucleonic component, using target thicknesses of 2 cm and 8.3 cm of lead, respectively, and *Cocconi and Cocconi-Tongiorgi* [1951] gave a value of $(40 \pm 13) \times 10^{-4}$ sec^{-1} cm^{-2} using a target thickness of 0.64 cm of lead. These estimates are not in good agreement with the present value. It is thought that most of the difference is due to the greater thickness of paraffin wax that surrounds the target in the standard monitor and therefore shields it from the large flux of low-energy neutrons in the atmosphere.

The Energy Response

(*a*) *Introduction.* From the results of experiments 1 and 2 and the analysis in the preceding section of this paper it is known that neutron and proton interactions can account for more than 90% of the neutrons detected by a monitor, that at all neutron and proton energies evaporation neutrons are produced according to an exponential production spectrum, and that the average number of neutrons produced increases in a definite way with the incident neutron and proton energy. It should therefore be possible, knowing the energy spectrums of neutrons and protons in the cosmic radiation at sea level, to predict the distribution of neutron multiplicities that a monitor will record, and then, conversely, to predict changes in the energy spectrum of nucleons from changes in the observed multiplicity spectrum.

If $N_n(E)$ is the differential energy spectrum of neutrons in the atmosphere at sea level, $P_n(E)$ the probability that a neutron of energy E will interact in the monitor, $I_n(E, \nu)$ the probability that a neutron of energy E will produce ν neutrons, and $B(\nu, m)$ the binomial probability that m neutrons will be detected out of ν produced, then the observed rate of detecting multiplicities of m neutrons is given by

$$R(m) = \int_0^\infty N_n(E) \cdot P_n(E)$$

$$\cdot \sum_\nu I_n(E, \nu) \cdot B(\nu, m)\, dE + \int_0^\infty \cdots dE \quad (2)$$

where the second term refers to the contribution due to proton interactions. All the quantities necessary to evaluate $R(m)$ for values of m ranging from 1 to 9 either are known or have been measured during experiments 1 and 2.

Figure 3 shows the neutron energy spectrum measured at sea level and a latitude of 44° north by *Hess et al.* [1959] for neutron energies ranging from thermal values up to 10 Gev together with the proton energy spectrum employed in the present calculation. The probabilities of interaction are taken to be those corresponding to the geometrical cross section, appropriately modified at proton energies less than 430 Mev when ionization loss limits the range of such protons in the lead target. (The present calculation ignores the energy lost by the protons due to ionization in the paraffin wax shield. The effect of this simplification is expected to be small, since more than 80% of the response of the monitor to low-energy incident nucleons can be attributed to neutron interactions.) The average number of neutrons produced in the monitor by incident protons for energies up to 100 Gev are given in experiment 1, and it is assumed that neutron interactions give similar numbers of neutrons. For incident protons a small correction has been applied to allow for the energy loss these particles undergo through ionization before they interact. At all the energies concerned, experiment 1 has shown that the neutron production spectrum is exponential, so that the probabilities $I(E, \nu)$ can be evaluated from the measured mean multiplicity that determines the exponent of the production spectrum.

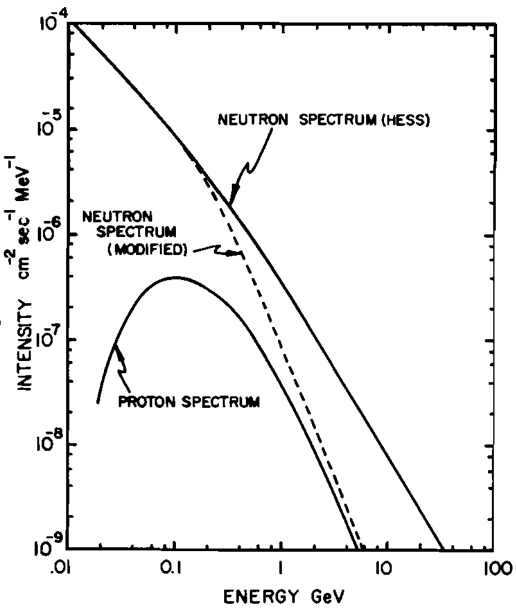

Fig. 3. The differential neutron energy spectrum at sea level given by Hess, and the modified Hess spectrum. The proton spectrum is shown for comparison.

(*b*) *The proton contribution.* The integrand of the second term in equation 2 is shown in Figure 4 as a function of the incident proton energy for values of m from 1 to 9. These curves give the differential contribution of proton interactions to the observed multiplicity rates, and their integrals with respect to energy give the total contribution to the observed daily rates. They are of the expected form in that the higher the multiplicity the higher is the proton energy giving the maximum contribution to the observed rate. At energies below 430 Mev the curves fall away rapidly as a consequence of both the energy loss in the target and the shape of the incident proton energy spectrum. At all energies the most probable detected multiplicity is one neutron, the production spectrum remaining exponential even up to the highest energies. If at energies greater than about 50 Gev the production spectrum were to alter in such a way that a single neutron was not the most probable number produced, the differential response curves of Figure 4 would begin to cross over each other at these energies. Experimentally, it is known that the production spectrum is exponential up to at least 25 Gev, and, because the rate of protons and neutrons of higher energy than this is so small at sea level, it is expected that this will not introduce significant errors.

(*c*) *The neutron contribution.* A similar calculation has been performed to evaluate the integrand of the first term of equation 2, in order to find the differential response curves for neutron interactions. The results of this calculation, giving the expected daily rates of the various multiplicities arising from neutron interactions, based on the neutron energy spectrum due to Hess, are shown as the dashed curve marked Hess in Figure 5. The sum of this curve and that due to proton interactions can then be compared with the observed multiplicity spectrum (curve *a* in Figure 1 after correction for multiplicities due to muon capture interactions). The predicted curve, however, overestimates the observed rates by an amount that increases with the multiplicity, until it is a factor of 4 too large at multiplicities of 9.

The predicted rates are based on a knowledge of the neutron and proton energy spectrums at

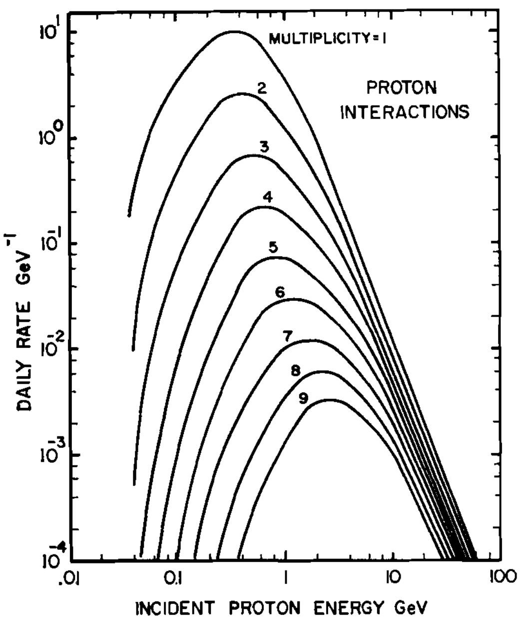

Fig. 4. Calculated curves showing the differential contributions to the various multiplicity rates as a function of the incident proton energy.

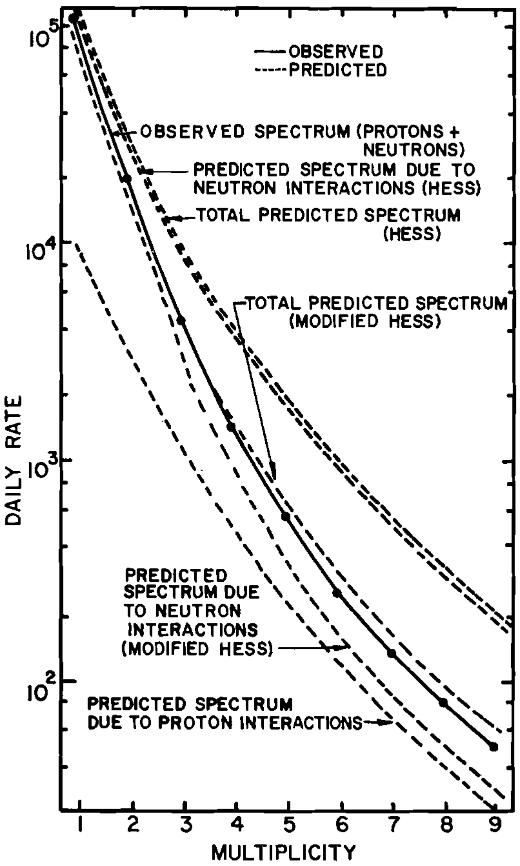

Fig. 5. A comparison between the predicted multiplicity spectrums due to neutron and proton interactions and the observed multiplicity spectrum. The predictions obtained using the neutron energy spectrum given by Hess and by the modified Hess spectrum are shown separately.

sea level, the variation of the average number of neutrons produced with energy, and the form of the neutron production spectrum. Of these, the neutron energy spectrum is the only quantity that has not been measured in experiment 1 or in a related experiment.

The neutron spectrum is given by Hess for energies ranging from thermal energies up to 10 Gev, but actually this spectrum is based on observations made at sea level for energies only up to about 500 Mev. From 10 kev to 1 Mev, neutrons in different energy ranges were detected by boron fluoride counters shielded by various thicknesses of paraffin wax. From a knowledge of the neutron detection efficiencies of these arrangements as a function of energy the neutron spectrum in the atmosphere was determined by a trial and error procedure which involved finding the shape of the spectrum that would uniquely reproduce the observed counting rates of the different detectors. At energies above 1 Mev the same method was employed, but in this energy region only two neutron detectors were used. One of them was an argon and carbon dioxide proportional counter lined with polythene, capable of detecting neutrons with a known efficiency from 100 kev up to 50 Mev; the other was a bismuth fission chamber, whose detection efficiency was only known up to 350 Mev but whose sensitive range extended up to energies of about 1 Gev. The problem was to adjust the shape of the neutron energy spectrum until the counting rates of these two detectors could be explained. As a guide to the shape of the spectrum at energies above 350 Mev, Hess used a result of *Messel's* [1954] theory of the nucleon cascade according to which the spectrum at sea level should have the same shape as the primary spectrum at the top of the atmospere for sea-level energies in excess of the geomagnetic cut-off. On the basis of this argument Hess extended the neutron spectrum to energies above 3 Gev according to a power law given by *Singer* [1958] for the primary spectrum, which has an exponent of 2.15.

On the other hand it is now known that the differential energy spectrum for protons at

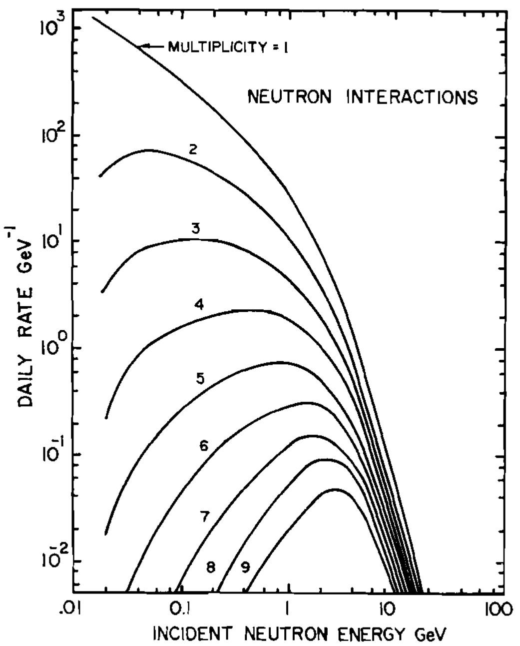

Fig. 6. Calculated curves showing the differential contributions to the various multiplicity rates as a function of the incident neutron energy according to the modified neutron energy spectrum.

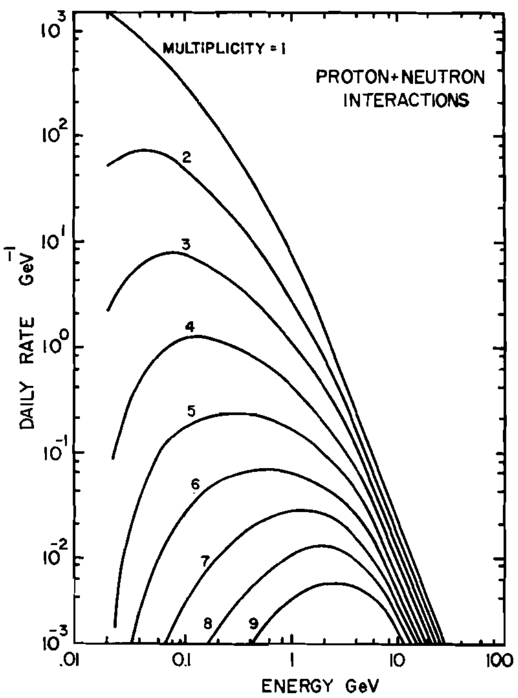

Fig. 7. Calculated curves showing the differential contributions to the various multiplicity rates as a function of the incident nucleon energy.

sea level is a power law with an exponent of about 2.6 from 10 Gev up to at least 100 Gev [*Brooke and Wolfendale,* 1964], and it is expected that the neutron spectrum should gradually become identical to the proton spectrum as the energy sweeps through this region. The neutron spectrum, therefore, should not fall away with an exponent of 2.15 at energies above 3 Gev, but its slope should gradually increase until it approaches a value of 2.6 at energies of the order of 10 Gev.

Figure 3 shows the neutron spectrum of Hess and the accepted proton spectrum for comparison. The dashed curve shows a modified neutron spectrum which agrees with the measurements of Hess up to 350 Mev and has the same form as the proton spectrum in the high-energy limit. The shape of this spectrum in the intermediate-energy range was chosen by trial and error for the reasons discussed in the following two paragraphs.

One point in favor of this modified neutron spectrum is that it is compatible with the intensity of the effective neutron component estimated from the present experiment. This intensity, $(7.5 \pm 0.6) \times 10^{-4}$ sec^{-1} cm^{-2}, indicates that the monitor is responding only to neutrons with energies in excess of about 50 Mev, which is reasonable in view of the thick paraffin shield surrounding the target. By the same argument the original spectrum of Hess suggests that only neutrons with energies in excess of 250 Mev can contribute to the observed neutron production. In experiment 1, however, protons with energy less than 250 Mev were frequently observed to interact in the monitor. Therefore 250-Mev neutrons that undergo no ionization loss in penetrating to the target should be able to interact also.

The differential response curves of the monitor for multiplicities of up to 9 neutrons, corresponding to the modified neutron energy spectrum, are given in Figure 6. These curves have features similar to those shown in Figure 4 for the proton interactions except that the maximums become increasingly broad as the multiplicity decreases until for multiplicities of one neutron there is no maximum at all. The predicted daily rates are given by the integrals of these differential curves down to a lower limit of 50 Mev, the approximate minimum energy needed by a neutron to penetrate the paraffin wax and to interact in the monitor. In Figure 5 the predicted multiplicity spectrum using the modified spectrum is compared with the observed multiplicity spectrum. This time there is good agreement between theory and experiment, suggesting that the modified neutron spectrum is approximately correct. Alternatively, adopting Hess's method of fixing the shape of the neutron energy spectrum by trial and error, it could be argued that the shape of the neutron spectrum in the relevant energy

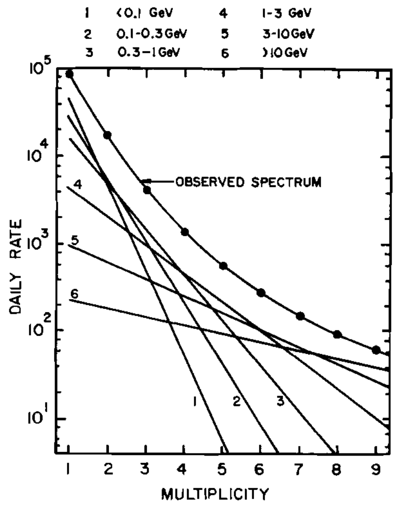

Fig. 8. An analysis of the multiplicity spectrum recorded by the monitor, showing how this spectrum is built up from the interactions of nucleons in six arbitrary energy intervals.

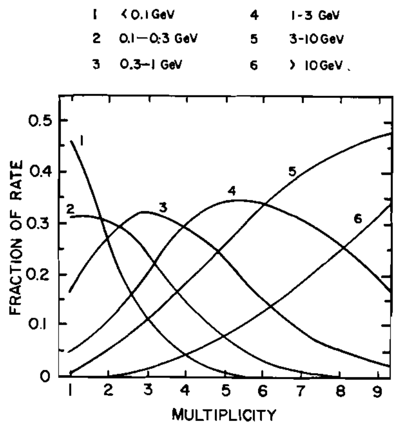

Fig. 9. Calculated curves showing the fraction of each multiplicity rate caused by the interactions of nucleons in six arbitrary energy intervals.

TABLE 2. Median Sea-Level Nucleon Energy Responsible for Observed Multiplicities

Detected multiplicity	1	2	3	4	5	6	7	8	9
Median sea-level energy, Gev	0.11	0.24	0.52	1.0	1.7	2.6	3.7	4.6	5.5

region from 350 Mev to 100 Gev must be such as to uniquely reproduce the multiplicity spectrum observed by the neutron monitor.

(*d*) *The total energy response.* Figure 7 shows the combined integrands of equation 2, giving the differential energy response of the monitor due to both neutron and proton interactions. To demonstrate clearly how the shape of the observed multiplicity spectrum is related to the energy spectrum of nucleons in the sea-level cosmic radiation, the integrals in equation 2 have been evaluated to determine the component spectrums of the total multiplicity spectrum due to interactions of nucleons in various energy ranges. For example, Figure 8 shows how the total spectrum is built up from the component spectrums caused by the interactions of nucleons in six energy intervals. In all these intervals, ranging from energies less than 100 Mev to energies in excess of 50 Gev, the component spectrums are straight lines on a semilogarithmic scale, their gradients decreasing with the incident energy as the average number of neutrons produced increases, but the number of events contributing to each component spectrum decreasing as the incident flux of nucleons falls rapidly away. Figure 8 illustrates how the shape of the low-multiplicity end of the total spectrum reflects the shape of the incident spectrum at energies less than 1 Gev, and how the shape of the high-multiplicity end depends on the shape of the incident spectrum at energies above 1 Gev.

The relation between the observed multiplicity rates and the incident nucleon spectrum is expressed in a more useful way by the curves shown in Figure 9, which give the fraction of the rate of each multiplicity caused by the interactions of nucleons in six energy intervals. For instance, 94% of the single neutrons observed are produced by nucleons with energy less than 1 Gev, whereas 87% of the multiplicities of seven neutrons are produced by nucleons with energies greater than 1 Gev. These results are summarized in Table 2, which gives the median nucleon energy corresponding to each detected multiplicity.

Application to Time Variations

It has been shown how the multiplicity spectrum detected by the standard monitor depends on the nucleon energy spectrum at sea level. Time variations in the primary spectrum incident at the top of the atmosphere cause changes in the spectrum at sea level and therefore also in the detected multiplicity spectrum. Therefore, as originally suggested by *Fieldhouse et al.* [1962], it is expected that changes in the multiplicity spectrum may be used to determine the behavior of the primary energy spectrum during periods of disturbance.

In recent years much information about the origin of the observed time variations in the cosmic-ray intensity has been deduced from worldwide observations on the total counting rates of neutron monitors. These observations provide detailed information on the energy dependence of the time variation over an energy range of the primary particles extending from about 1 to 15 Gev (the geomagnetic cutoff at the equator). However, the neutron monitors also respond to primary particles with energies in excess of 15 Gev, and the results of this paper suggest that the phenomenon of multiple neutron production provides a method of distinguishing the part of the response of a neutron monitor caused by the primary radiation with energy in excess of 15 Gev. In fact, since the average number of neutrons produced in the monitor steadily increases with nucleon energy, it might be expected that the behavior of the detected multiplicity spectrum would reflect the energy dependence of the time variation over the whole range of primary energies to which the monitor responds.

Acknowledgments. One of us (E. B. Hughes) is grateful to the University of Leeds for the award of a Junior Ellison Fellowship. Both of us are grateful to Professors G. D. Rochester and J. G. Wilson for their interest in this work.

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THE PALEOGEOGRAPHY OF AUSTRALIA IN RELATION TO THE MIGRATIONS OF MARSUPIALS AND MEN*

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Introduction

Australia is a compact subcontinent of some 3,000,000 square miles which has retained its essential size and shape for the whole of the Cainozoic Era. To the nearest 100,000 square miles, Australia without New Guinea is the same size as the United States without Alaska. In build, it consists of a massive Precambrian shield of great stability, around the edge of which is a border of less stable younger rocks. This border is slight to the north, narrow to the west and south, but wide in the east where the Tasman Geosyncline covers the whole eastern side of the continent in addition to considerable areas of the contiguous seas. The Precambrian shield, the Tasman Geosyncline and the associated Great Artesian Basin ($>$600,000 square miles) are all features of world importance.

In this paper a conscious effort has been made to present evidence that is not dependent on either the hypothesis of stable continents or drift.

Physical Change Incited Biologic Change

During the Lower Cretaceous, Australia was invaded by a central sea which divided the continent into a group of islands. The largest of these was to the west and so nearest to Asia, the only known source for terrestrial migrations. This epicontinental sea was comparatively shallow, but the sinking floor of the Great Artesian Basin resulted in the deposition of marine strata up to one mile thick. Below and above the marine beds are formations of nonmarine rocks. This flooding of the continent had some very important effects, among which were:

(1) Nearly to halve Australia's land mass.
(2) Thus, to limit severely the area available for terrestrial plants and animals.
(3) To destroy completely some habitats.
(4) To modify the climate to a marked degree so that areas formerly continental became insular in climate.
(5) Thus, to alter significantly the environmental pressures on the genetic constitution of plants and animals, i.e., to change the direction of evolution for many species.
(6) To increase the difficulty of the migration of most animals and plants because of the drowning of land bridges and the widening of water barriers.

*This paper, illustrated with slides, was presented at a meeting of the Section on October 4, 1965.

A factor of considerable importance for our inquiry is that the six important effects named above were of very wide occurrence in the world. Australia was not the only large land mass to receive epicontinental seas during the Cretaceous. Indeed, it was such a widespread phenomenon round the world that a global explanation is required for it. The Cretaceous marine transgression was probably the greatest in all known geological history, but the advances of the sea were not all at the same time. The pressure of change in the physical world set the stage for change in the biologic world. The terrestrial climate was warm. Glaciation was unknown, and rich vegetation is recorded even from arctic areas.

The Three World Revolutions

When the epicontinental sea withdrew from Australia in the Upper Cretaceous, that continent assumed the general shape and extent which (with modifications) has persisted to the present. This gradual retreat of the oceans from the land masses in the Cretaceous is also a worldwide phenomenon requiring a global explanation. In this connection it may be noted that the floor of the Pacific Ocean (largest of the seven oceans) has yielded no rocks older than Cretaceous. The rocks from the flat tops of guyots (which are scattered over millions of square miles) are all Cretaceous or Cainozoic. The rocks recovered from the walls of submarine canyons are generally no older than Cretaceous, as are those from the oceanic submarine ridges. The flexing of the ocean floors necessary to account for the planated tops of guyots, now thousands of feet below the surface of the ocean, must have deepened the oceanic reservoirs, contributing to the withdrawal of the epicontinental seas. However, all the transgressions did not occur at the same time. For example, the oceanic advance was chiefly Lower Cretaceous in Australia but Upper Cretaceous in North America. So little is yet known of these matters that we can only make suggestions as to the mechanisms involved. However, it is clear that the retreat of oceans from the continents created extensive new areas of land, thus fundamentally changing the dynamics of both the hydrosphere and the biosphere.

One of the most significant periods, the Cretaceous lasted some 70,000,000 years (a little longer than the Cainozoic Era; Casey, 1965). Indeed, there is ample evidence for asserting that it is the most significant, for during its span of time there occurred three transformations of major importance for world history. In its own right, each of these processes was a factor of major importance, but the fact that the three processes are also more or less synchronous accounts for the remarkable changes of that period. They are:

(1) *The success of the flowering plants (angiosperms)* or the plant revolution. With the flowers came those insects dependent on them. The modern broad-leaved plants and hardwood forests evolved.

(2) *The success of animals with greater temperature control, greatly increased brain power and milk feeding of the young* or the mammal revolution. In the Mesozoic the reptile was "king of the beasts," and in the Upper Cretaceous there was the change to the condition in the Cainozoic when the mammal was "king of the beasts."

(3) *The major changes in the relationships of land and sea,* to which reference has already been made, or the ecological revolution. The major increase in the land area provided vast new opportunities for the development and distribution of new plants and animals. Conversely, the reduction in the extent of the oceans made it easier for species to cross from one land mass to another; the lowering of ocean level created new land bridges.

Although the angiosperms and mammals originated earlier in the Mesozoic, it was in the Cretaceous that they "lay conquest to the earth." By the Upper Cretaceous, there were new animals and new plants on a greatly enlarged land surface with new migration possibilities. New ecologies were also created by earth movements in the late Cretaceous. So it was against this background of remarkable world events that Australia achieved its present continentality and became, *par excellence,* the home of the marsupials, the monotremes and the Myrtaceae (eucalypts and related forms).

Let us now examine (1) the flora and fauna of Australia before the migration of mammals, (2) the time of this migration and (3) the changes following this migration that led eventually to the coming of man to Australia.

Cretaceous Flora and Fauna of Australia

Biologists are impressed by the fact that the present fauna and flora of Australia are so different from those in contiguous areas. The opposite was so in the Cretaceous. In the Cretaceous, the flora and fauna of Australia (and previously) have many close parallels with those of New Zealand, 1,200 miles across the ocean to the east. The flora of Australia in that period is very like that of the Raj Mahal beds in India; there are many forms the same or very close to those found in Europe. "The biota of the hemispheres had much more in common than in this age of flowering plants" (Cranwell, 1964). The present flora and fauna of Australia are markedly indigenous, while those of the Cretaceous and earlier tended to be ubiquitous.

The Cretaceous marine beds of Queensland have yielded ichthyosaurs and plesiosaurs. The massive sauropterygian *Kronosaurus* is the world's largest known marine reptile. A sauropod about 50 feet in length *(Austrosaurus)* has been described. Two genera of turtles are known, *Cratochelonus* being about 12 feet long. The abundant evidence in bones and tracks of reptiles in northern Australia contrasts with the poverty of remains in the south of the continent, e.g., Victoria. Over 5,000 feet of Lower Cretaceous nonmarine rocks are known in Victoria, and they are well exposed in sea cliffs, stream courses and road cuttings. The outcrops have been closely examined by local and overseas geologists, yet the only reptilian remains found were the claw of a carnivorous dinosaur (? *Megalosaurus*) and the humerus of what is probably "a Saurischian dinosaur and a small Theropod." This fossil was determined by E. H. Colbert (personal communication) and has not been recorded before. These beds have produced teeth and scales of the lung fish *Ceratodus,* shoals of the plankton-eating leptolepid fish (Gill, 1965, plate 4) and numerous insects and other arthropods. The last named include *Mesolimulus,* a king crab not previously recorded from Australia. It occurs with insects (including aquatic nymphs of stoneflies, mayflies and dragon flies, determined by E. F. Riek), leptolepid fish and numerous plants, i.e., a completely freshwater environment. Paleogeographic reconstruction shows that the site was miles from the sea. Either this *Mesolimulus* was a freshwater arthropod or a marine arthropod that came up from the sea to spawn in fresh water.

It may be that the lack of reptiles in Victoria is a latitudinal effect, the orientation of the continent having been much as it is at present. Schwarzbach (1963, Figure 96) shows an arid zone in eastern Asia in the Lower Cretaceous with a tropic zone north of India. The climate in Victoria may have been cool and, thus, the reptile population was limited. No tracks of reptiles have been recorded in Victoria. A little work has been done on oxygen isotope paleotemperature measurements (Dorman & Gill, 1959; Bowen, 1961; Lowenstam, 1964) of Australian Cretaceous fossils, but the small number of analyses and the variant results obtained mean that an adequate picture of temperature changes has not yet been obtained. It is clear from the plentiful plant remains, the sedimentary structures, the abundant carbon (including thick seams of coal) and the size of preserved trees that the climate was humid over considerable areas.

Some interesting changes have taken place in certain elements in the flora. For example, at the present time there is a dwarf recumbent conifer found only on the cold, windswept, high plains of Western Tasmania, but in the Lower Cretaceous this genus grew as a tall forest tree in Western Victoria, as is shown by silicified logs. Wood has been discovered that shows every cell of the structure, allowing comparison with the living *Microcachrys*. The wood structure was studied by H. D. Ingle of C. S. I. R. O.* Division of Forest Products. In the same formation as the silicified wood is pollen of a type very similar to that of the living plant, and so it has been named *Microcachrydites* (Cookson, 1947). Balme (1964) uses this fossil to name an Assemblage.

Angiosperms have been found in the Lower Cretaceous of Victoria (Medwell, 1954), but they are rare. Apparently, it was not until the Upper Cretaceous that they became common. Cookson (1964) has outlined what is known of the early records of angiosperms in Australia. In spite of extensive search by local geologists and by teams of workers from the United States, no monotreme or marsupial remains have been found in Cretaceous rocks in Australia.

When Did the Marsupials Migrate?

The similarity of Mesozoic terrestrial and freshwater floras and faunas (as far as they are known) in Australia, New Zealand and South Asia suggests fairly free migration between the Asian continent and the Australian subcontinent. This appears to be the basic truth behind the concept of Gondwanaland. After the Cretaceous Period the faunas and floras of Australia, New Zealand and Asia, respectively, become progressively dissimilar, suggesting the mutual severance of these areas and the maintenance of that severance. There are two periods when such severance can be deemed to have occurred, viz. (1). There is unmistakable evidence in Australia of earth movements in the late Cretaceous and early Tertiary during the Bass Strait Epoch (Gill, 1964). It may well be that at this time of widespread instability the Java Arc and the associated ocean deep began to form, thus achieving the severance of the

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Australasian area from Asia. These tectonic movements appear to belong to a series of world movements that initiated the uplift of the Great Dividing Range of Australia, the Rocky Mountains of North America, the Andes Chain of South America and other important mountains. (2). At the very end of the Lower Cretaceous in Australia, marine sedimentation was cut off over most of the continent. The movements involved in this change may be responsible for severing the migration route. Thus, it would appear that these tectonic movements in S. E. Asia and Australia exercised the fundamental control on the migration route from Asia to Australia.

On present information it would appear that marsupials did not migrate to Australia in the Lower Cretaceous because:

(1) There are no marsupial fossils of that age in Australia (a negative argument without much force; none has been reported from either the Mesozoic or Cainozoic of Asia, but as marsupials were present in both Europe and America, their presence in the intervening area of Asia can be surmised).

(2) The paleogeography suggests a widening of water barriers due to a higher sea level which flooded Central Australia and probably the means of access of the marsupials.

On this hypothesis, the first marsupials reached Australia in the Upper Cretaceous or early Tertiary. The migration was earlier than the Oligocene because a fauna of that age is known from Central Australia (Stirton, 1961), if the dating is correct. Moreover, the phalanger *Wynyardia* was collected from Oligocene marine strata at Fossil Bluff near Wynyard in northern Tasmania (Spencer, 1900; Wood Jones, 1930; Gill, 1957; Ride, 1964).

The age of the earliest discovered marsupial or marsupials provides a minimum age for migration, but further assistance can be derived from the nature of the fauna itself. The fossils from Central Australia belong to the families Dasyuridae, Phascolarctidae, Macropodidae and Diprotodontidae, while the fossil from Tasmania belongs to the Phalangeridae, or (according to Osgood, 1921, and Ride, 1964) to the Wynyardiidae. If the dating is correct, at least five families of marsupials belonging to more than one suborder existed in the Oligocene (TABLE 1). This high degree of divergence of the earliest reported marsupials in Australia, all belonging to families found only in the Australian area, means that the ancestral marsupials from which they sprang must have arrived in the country a long time before. The earliest known Australian marsupials (except the Dasyuridae) are quite different from any fossil marsupials known from other parts of the world. Even allowing for the rapid radiation that apparently occurred after the earliest marsupials reached Australia, there is not enough time to account for the divergences that happened unless the time of migration is put back to the Upper Cretaceous. It may also reasonably be argued that, as the marsupials had to enter on a land connection that was destroyed before the placentals could appear on it, the time of entry must have been pre-Tertiary. If the marsupials and the placentals coexisted in S.E. Asia and were competing as they did in Europe and in N. America, then their time of entry into the Australian region must have preceded the time of coexistence; i.e., the entry time and the severance of the route must have been very early. Simpson (1953, 1961) suggests that the marsupials reached Australia by opportunistic island-hopping.

TABLE 1

AUSTRALIAN TERTIARY MARSUPIALS

Age	Dated by Marine Fossils and K/A	Dated by Extrapolation
Oligocene	*Wynyardia bassiana* Spencer, 1901	*Perikoala palankarinnica* Stirton, 1957 Dasyurid, Stirton, 1961 Diprotodontid, Stirton, 1961 Potoroin, Stirton, 1961
Miocene	Diprotodontid (small), Stirton, 1957 Diprotodontid (large), Stirton, 1957	
Pliocene	Sthenurin, Stirton, 1957 Phalangerid, Stirton, 1957 (= Potoroo Ride, 1964). Chiroptera non Phascogalinae, Turnbull *et al.*, 1965 (personal communication) Macropodinae, Turnbull *et al.*, 1965 Phalangerinae, Turnbull *et al.*, 1965 Pseudocheirinae, Turnbull *et al.*, 1965 Burramyinae, Turnbull *et al.*, 1965 Paramelid, Turnbull *et al.*, 1965 (personal communication)	*Glaucodon ballaratensis* Stirton, 1957 *Vombatus pliocenus* (McCoy) 1874 *Thylacoleo crassidentata* Bartholomai, 1962 *Ischnodon australis* Stirton, 1955 *Priotemnus palankarinnicus* Stirton, 1955 *Meniscolophus mawsoni* Stirton, 1955 Macropodid, Stirton, 1961 Sthenurin, Stirton, 1961 Marsupial humerus, Warren, 1965 (in press)

Taking all the evidence together, limited and somewhat oblique though it may be, an Upper Cretaceous migration appears to be the best working hypothesis. Thus, it seems that while the white chalk was being deposited in Europe, while a great seaway bisected North America, while the early mid-Pacific seamounts were being planated and before there were any horses, the primitive marsupials first entered Australia. The new continent, recently emerged from the sea, offered a vast area for distribution and a vast array of habitats for differentiation. The marsupials "conquered" the continent and hold it still, because placental competition is limited.

Evolution of the Present Australian Fauna and Flora

Visitors to Australia are impressed by the dominance of the eucalypts and wattles *(Acacia)* in the flora. In 1836, Darwin, on visiting New South Wales, wrote "The extreme uniformity of the vegetation is the most remarkable feature of the landscape of the greater part of New South Wales" (Darwin, 1889, p. 315). These trees contrasted strongly with those known elsewhere in the world. Likewise, the marsupials and monotremes were so different from the placentals of other countries that they appear to be survivors from the Mesozoic. Thus, Australia came to be widely regarded as a country with an age-old fauna and flora, a biological asylum where ancient forms of life have survived without much change, because they were free from competition with the more advanced forms from other parts of the earth. Much remains to be learned about the post-Cretaceous succession of life in Australia, but the view referred to above is now demonstrably incorrect.

Tertiary fossil leaves found in lacustrine deposits in many parts of Australia were referred to as *Eucalyptus* by early workers, but these identifications cannot now be sustained. The records from other continents are also erroneous. It took the author ten years' search to demonstrate the presence in Australia of *Eucalyptus* in pre-Pliocene strata. A silicified log, 40 feet long, was discovered in the freshwater beds of the Derwent Graben at Hobart in Tasmania. Where dated, this formation was found to be Yallournian (Oligocene) in age (Gill, 1962). The determination of the Hobart tree has been confirmed by others, e.g., L. Pryor (1959). In brown coal of the same age at Altona in Melbourne, Victoria (under a Miocene marine bed), a piece of collapsed wood was found that probably belongs to *Eucalyptus*. These determinations were made by H. D. Ingle of the Wood Structure Section of the C.S.I.R.O. Division of Forest Products. While Myrtaceous pollen occurs in early Tertiary strata, *Myrtaceidites eucalyptoides* is not known until the Pliocene. From the many available sites in the southern half of mainland Australia, from eastern Queensland and from Tasmania, there is very little evidence of *Eucalyptus* in pre-Pliocene times. For these areas, at least, it would appear that this genus was rare in the warm humid climates of those times (Gill, 1961 *a, b*) but came to prominence when the drier conditions of the Quaternary prevailed. No *Acacia* earlier than Pliocene is known, although the tree is now so common.

At Hamilton in Western Victoria, an Upper Pliocene landscape preserved under basalt shows the transition stage from the conifer-beech *(Nothofagus)* flora of the Tertiary to the eucalypt-wattle flora of the Quaternary (Gill, 1957). At this site there are the roots of a stand of *Phyllocladus* (not now found on the Australian mainland) wiped out by the basalt flow. Potassium/argon dating of the basalt gave 4.35 million years (Turnbull, *et al.*, 1965). A high proportion of the Tertiary flora consisted of trees, but trees are now limited to about a sixth of the continent. The flora over the bulk of Australia at the present time is xeric. Perhaps the northern deserts of Australia are the site where *Eucalyptus* evolved, and from which it claimed the continent when the conditions were suitable. The hypothesis is put forward that there was an original radiation in the Upper Cretaceous-Lower Tertiary following the migration of the angiosperms to Australia, and then another when *Eucalyptus* and *Acacia* came to dominance in the Pliocene-Quaternary. Some 600 living species of *Eucalyptus* have been described and some 400 living endemic species of *Acacia*. The eucalypt species, in particular, are very difficult to define, and hybridization is rife. It is suggested that this intense speciation, taxonomic instability and lack of maturity in species is a function of radiation. Thus, the familiar eucalypt-wattle flora of Australia is not a Cretaceous flora persisting to the present, but is a novelty from the viewpoint of geological history.

In a letter to Sir Charles Lyell, Darwin wrote: "I quite agree with you on the strange and inexplicable fact of *Ornithorhynchus* having been preserved" (F. Darwin, 1887, 2:340). Most biologists since Lyell and Darwin have, likewise, been impressed. If any survivors of the Age of Reptiles still remain on the earth, surely these are they. Yet, recent researches show that in the Pleistocene the larger New Guinea echidna with the curved beak *(Zaglossus)* was the dominant ant-eater and not the present day *Tachyglossus*, although the latter was also present. *Zaglossus* appears to be adapted to the more humid conditions of New Guinea, while *Tachyglossus* is typically an inhabitant of rather dry country. So even with the monotremes, the fossil record shows that there have been marked changes in occurrence since the Pliocene. The present monotremes are not age-old taxa persisting since the Cretaceous, even though the *grade of organization* may be described as Mesozoic. One of the exciting paleontological discoveries yet to be made is the remains of the earlier monotremes.

There is a similar changing history for the marsupials. There has been nearly as much evolution among the marsupials as among the placentals elsewhere. The kangaroo may be regarded as the ecological equivalent in Australia of the equids and bovids of other continents. Many of the present grassy plains and savannah woodlands were covered with forests in the Tertiary, and the drier conditions of the Quaternary (or much of it) led to the widening of the plains and thus to the extension of kangaroo habitats. The emergence of grasses in the Tertiary is as important for Australia as it is for other lands. Also, whereas the trees of the Tertiary forests had closed crowns, the eucalypts have open crowns which provided new opportunities for the evolution of volant forms of possums. Three lines of phalangers developed volant forms.

Placental Migrations

When Europeans arrived in Australia, they discovered that four groups of nonmarine placentals had managed to migrate to the land of the monotremes and marsupials, i.e., the bats, the rats, the dog (dingo) and the aborigines. The bats flew into Australia. The rats are a very varied group. Taxonomists differ in the number of genera they employ to classify the rats of Australia, but the number is of the order of 25. Over 80 per cent are indigenous, and whole families are limited to the Australian area. On the other hand, the ubiquitous *Rattus* is found in Australia, too. Thus, it may justifiably be concluded that there has been a number of migrations, some so old that indigenous families have arisen and some as recent as the arrival of *Rattus*. The rat is a successful migrant because it can burrow in a log floating across the seas and survive. A hardy animal, it readily adapts to new conditions.

Finally, we come to the migration of man, who (it is believed) brought his dog, the dingo, with him. But there was more than one migration of men, and the dog did not come with the earliest of them.

Paleogeography and the Migration of the Australian Aborigines

From a geological point of view, New Guinea and Tasmania are parts of the Australian continent. Unless a map has bathymetric contours, it does not give the right impression of the relationship of New Guinea to mainland Australia. The seas separating Tasmania and New Guinea from the mainland are very shallow. Indeed, Tasmania had no distinctive existence in the Cretaceous or earliest Tertiary. Bass Strait (separating Tasmania from the Australian mainland) is a Cainozoic phenomenon (Gill, 1962). The same probably applies to New Guinea. During the Quaternary, the eustatic changes of sea level had much to do with the making and breaking of migration routes. During the last glaciation, on present evidence, the sea retreated to its lowest level, probably as far as the edge of the continental shelf. Migrants crossing to Australia at that time had only half as far to go from the Banda Arc to New Guinea, as they would under present conditions. The Arafura Sea and Torres Strait were practically absent. The migrant, having then arrived in New Guinea, would find continuous land as far south as the southern tip of Tasmania. Much of the central area of Australia that is now arid or semi-arid was temperate in climate, so that migrants could travel by the east coast, the centralian or the west coast route. This time of lowest sea level was something like 20,000 to 17,000 years ago. Mulvaney (1964) has found evidence of aboriginal life in a Queensland cave which was dated by radiocarbon as being 16,000 years old. At the same site as that which yielded the Keilor Cranium near Melbourne, Victoria, a deposit was found at a lower stratigraphic level that consisted of an oval area of burnt ground associated with wood charcoal, bone charcoal and bones of food animals in the same way as in a midden, i.e., with random orientation, and certainly not waterlaid. Only man can achieve an aggregation of such materials. A radiocarbon date of the charcoal gave 18,000 years. Australian anthropologists were slow to accept this as an aboriginal site because there were no skeletal remains and no implements, although it is common for middens (especially small ones) to have neither. No one has yet been able to account for this association of materials in any other way. The late F. E. Zeuner and some other eminent visitors considered the site indubitably one of human occupation. If we accept this as the author does, then there is evidence of human occupation in Australia at the time of lowest sea level and, thus, easiest migration. It would appear that once again paleogeography is significant for understanding a migration.

Summary

In the Lower Cretaceous, Australia's biggest marine transgression flooded the continent and apparently drowned the land connection with Asia. In the Upper Cretaceous, Australia achieved its present continentality and, it is believed, received migrations of angiosperms, monotremes and marsupials. The marine retreat and extensive earth movements on the new continent provided many and extensive habitats in which the migrants radiated. Conifer-angiosperm forests occupied, at least, the major part of the continent. In the Pliocene the Tertiary flora was replaced over wide areas by a *Eucalyptus-Acacia* flora leading to a radiation in these genera and associated animals; the rise of the Gramineae was also significant. This radiation was likewise synchronous with land movements. Pleistocene lowering of sea level created new possibilities of migration, and man arrived with his dog, the dingo.

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