THE COSMIC RAY NUCLEONIC COMPONENT: THE INVENTION AND SCIENTIFIC USES OF THE NEUTRON MONITOR

(Keynote Lecture)

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Abstract. The invention of the neutron monitor pile for the study of cosmic-ray intensity-time and energy changes began with the discovery in 1948 that the nucleonic component cascade in the atmosphere had a huge geomagnetic latitude dependence. For example, between 0° and 60° this dependence was a $\sim$200–400% effect – depending on altitude – thus opening the opportunity to measure the intensity changes in the arriving cosmic-ray nuclei down to $\sim$1–2 GeV nucl^{-1} for the first time. In these measurements the fast (high energy) neutron intensity was shown to be a surrogate for the nuclear cascade intensity in the atmosphere.

The development of the neutron monitor in 1948–1951 and the first geomagnetic latitude network will be discussed. Among its early applications were:
(1) to prove that there exists interplanetary solar modulation of galactic cosmic-rays (1952), and;
(2) to provide the evidence for a dynamical heliosphere (1956).
With the world-wide distribution of neutron monitor stations that are presently operating ($\sim$50) many novel investigations are still to be carried out, especially in collaborations with spacecraft experiments.

1. Introduction

In the late 1930s and immediately after World War II conclusive evidence was obtained from diverse experiments that the cosmic radiation reaching the top of Earth's atmosphere produced nuclear interactions deep in the atmosphere. For example, nuclear interactions were found in photo emulsions as early as 1937 (e.g., Blau and Wambacher, 1937). Disintegration products were identified in the period 1940–1946 using Ilford emulsions (e.g., Lattes *et al.*, 1947) and cloud chambers. The discovery of the mesons with short half-life and fluxes of neutrons with $\sim$15-min half-life provided assurance that they were the product of nuclear disintegrations in the atmosphere. The low and high energy neutron density as a function of atmospheric depth was measured – mainly by Korff and collaborators with balloons (e.g., Korff, 1939; Bethe *et al.*, 1940) and in aircraft by Agnew *et al.* (1947). Finally, it was shown by Schein *et al.* (1941) in a balloon flight that the incident cosmic radiation was composed – at least in part – of high energy protons.

Thus, by 1946 it was becoming clear that the energetic nuclear disintegration product protons and neutrons in the atmosphere would produce further, succes-

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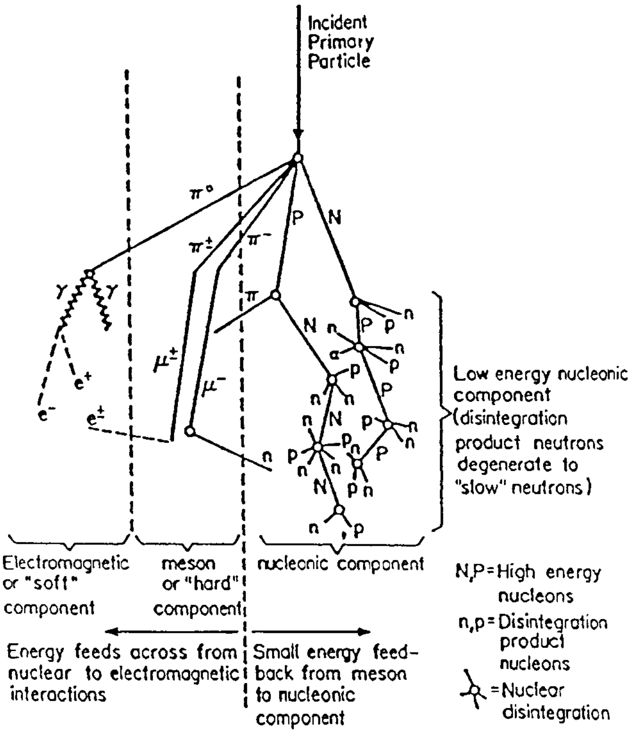


Figure 1. Schematic representation of the typical development of the secondary cosmic radiations within the atmosphere arising from an incident primary particle (Simpson *et al.*, 1953b).

sively lower energy nuclear disintegrations to form a nuclear cascade or secondary nucleonic component, as illustrated in Figure 1.

2. Discovery of the Fast Neutron Latitude Dependence

My initial research goals after World War II were to investigate the energy spectrum and origin of the cosmic rays. Since the magnitude and penetration of the nuclear cascade in the atmosphere must be a function of the incident cosmic-ray nucleon, I decided in 1946 to investigate the dependence of the nucleonic cascade on the incident cosmic-ray nucleon energy. This dependence was not known because the experiments cited above had been carried out at more or less similar high latitudes – indeed, many of the publications did not state the latitudes of the measurements!

I decided to use the geomagnetic field cut-off effect as a function of latitude for analysis of the incident 'primary' cosmic-ray spectrum at the top of the atmosphere through measurements of the nucleonic cascade. The nuclear disintegration intensity in the atmosphere was to be determined by its surrogate, the fast neutron density. Only fast neutrons – on the average above 10's of MeV – would be measured since much lower energy neutrons (the 'slow' neutron flux) would include a

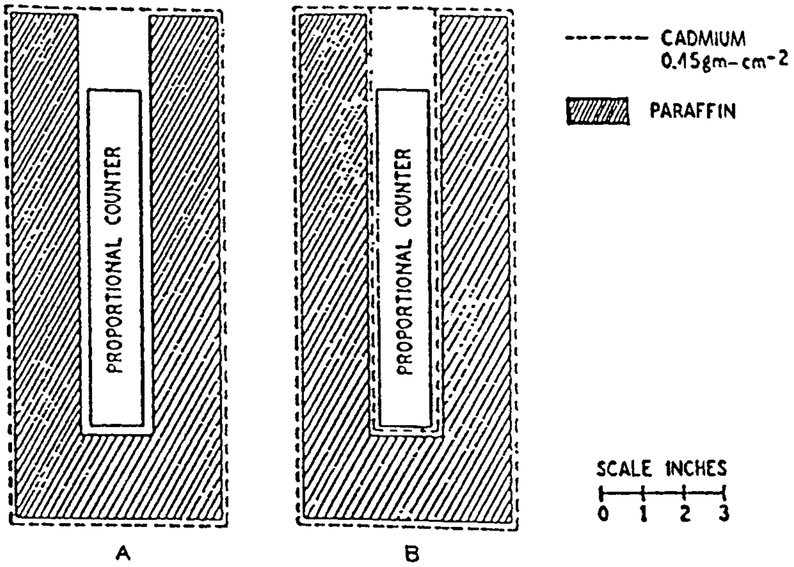


Figure 2. Cross sections of BF_3 proportional counter geometries used to measure neutron intensity. By inserting the cadmium thimble around the counter, as shown in (B), the counter background may be measured (Simpson, 1951).

thermalized neutron component highly dependent on variable local conditions. An additional constraint for the detection of the fast neutrons was the non-detection of the meson and electron components at all energies.

All these conditions were met by BF_3 gas proportional counters with the enriched isotope ^{10}B that has a neutron capture cross-section inversely proportional to the neutron velocity,

$$^{10}B + n \to ^{11} B^* \to ^7 Li + ^4 He^{++} + Q \, . \tag{1}$$

By setting the pulse height threshold so that only ^{4}4He^{++} pulses are detected in the proportional counter, all electromagnetic components (Figure 1) are not recorded due to their small ionization loss in the counter gas. These $^{10}BF_3$ proportional counters enriched in ^{10}B were perfected during World War II in the Manhattan Project.

For the initial latitude measurements in 1946–1947 I adopted the geometry shown in Figure 2. Since ^{113}Cd has a slow neutron capture cross-section of approximately 20 000 barns, only fast neutrons penetrating the Cd shield in Figure 2(a) – after slowing down in the paraffin moderator – will be captured by ^{10}B. Design and measurement details are described by Simpson (1951). The instrumentation is similar to that used by the Los Alamos group (Agnew *et al.*, 1947).

In order to confirm earlier measurements of the latitude dependence of the charged particle components by other investigators, two vertical, three-fold G-M counter telescopes with 20 cm lead absorbers were also accompanying the fast neu-

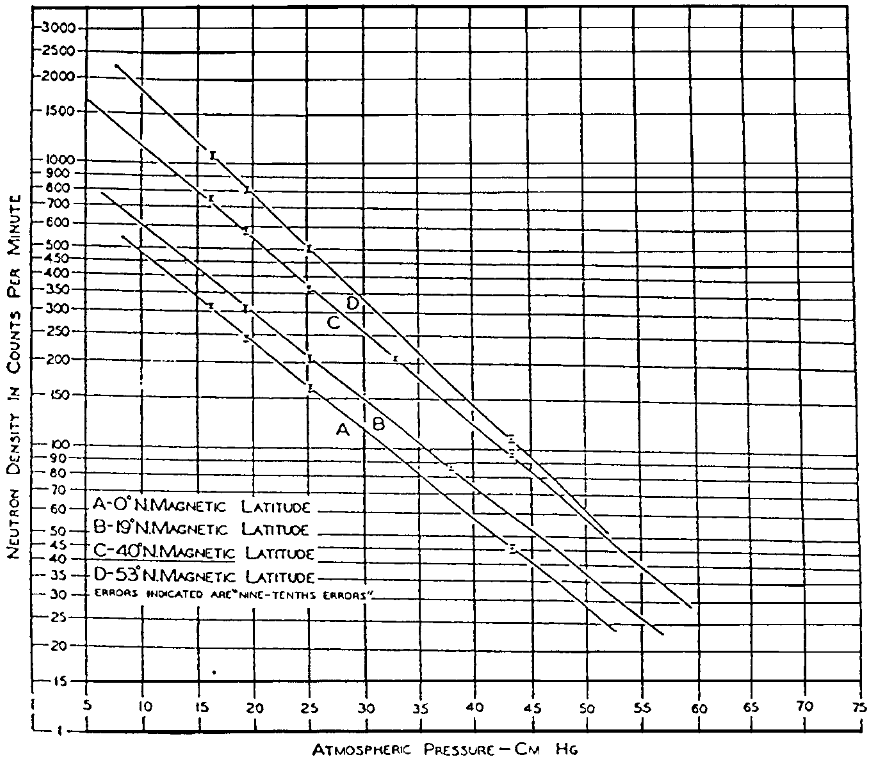


Figure 3. The relative fast neutron density in the atmosphere. The errors shown are such that there is a 0.9 probability that the measured value is within the range of the indicated error (Simpson, 1948).

tron instrumentation during the first latitude flights (see Simpson, 1951, Appendix II, for details).

In early 1947 all I needed was suitable transportation. By good fortune I learned that the Office of Naval Research, along with the U.S. Air Force, had established a B-29 bomber base for research purposes in the desert at Inyokern, China Lake, California. I quickly convinced them that we needed to make a latitude survey at fixed pressure altitudes and arranged with them to carry my instruments and myself. The three B-29 aircraft at the base were modified to fly at high altitudes with special propeller controls and for brief periods of time could attain altitudes of 41 000 ft. (12 500 m).

Since I was a lone investigator, except for my machinist instrument builder, it was not long before we found ourselves at Inyokern equipped with oxygen masks and parachutes, all ready to take data in flight. On looking back on those days I must admit that only now I realize how risky the whole adventure was. Instructions for flight? "If you have to bail out at 30 000–40 000 ft. be sure to count slowly to ten before you pull the ripcord (on your left shoulder pad) or else you will freeze to death at high altitude."

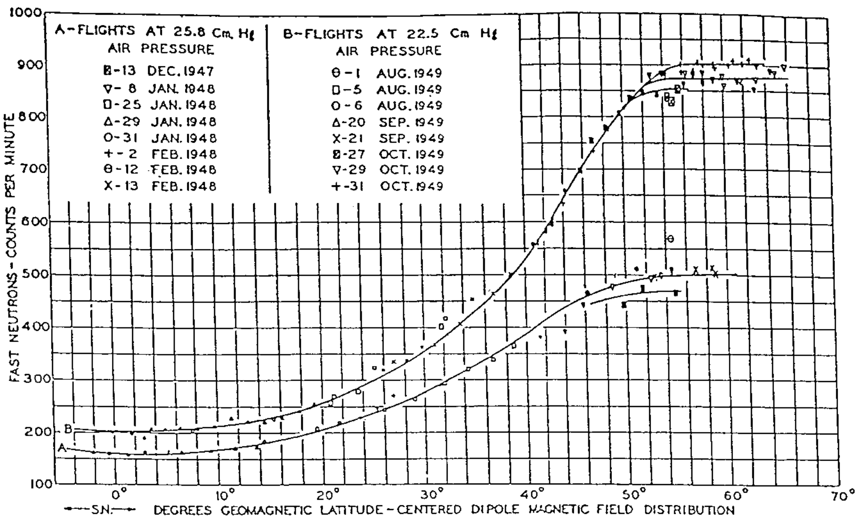


Figure 4. Latitude dependence of fast neutrons at (A) 27,000 ft. and (B) 30 000 ft. Several points lie off the curve between 20° and 40° owing to errors in navigation. The family of curves at high latitude for (B) show the change of intensity between October 27 and 31, 1949 (Simpson, 1951).

The fast neutron density in the atmosphere was obtained as a function of pressure altitude at 0°, 19°, 40°, and 53° North geomagnetic latitude, as shown in Figure 3 (Simpson, 1948). The measurements at 53° were in agreement with earlier free atmosphere measurements. However, these data also display surprisingly large geomagnetic latitude dependence. This latitude effect is clearly shown in Figure 4, for two constant pressure altitudes. The nucleonic component latitude effect was 300–400%.

The unshielded ion chamber or vertical counter telescope with no absorber, as measured by H. V. Neher on the same flights in June 1948, displayed the known, small latitude dependence shown in Figure 5 (Simpson *et al.*, 1953a, b). The routes of the B-29 aircraft (and later the RF80 jets) are shown in Figure 6.

It immediately became apparent from this discovery that changes in the incident low energy cosmic-ray proton intensity down to 1–5 GeV could be investigated continuously at high latitude and low energies for the first time. A new, low energy window was opened to study changes in the cosmic-ray energy spectrum, as sketched in Figure 7.

3. The Development of the Neutron Monitor

In early 1948, I was curious as to why the nucleonic component intensity changed at high latitudes from flight to flight, especially above the ‘knee’ imposed by the geomagnetic field cut-off (Figure 4). Clearly the best way to investigate the origin

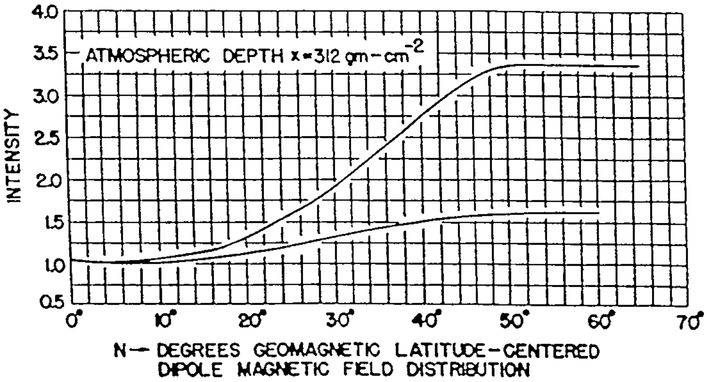


Figure 5. The lower curve represents the latitude dependence for either an unshielded ion chamber or vertical counter telescope with no absorber as measured by H. V. Neher. The upper curve represents the disintegration product neutron production also normalized to $I = 1$ at $\lambda = 0°$. The data for both curves were obtained in June 1948 (Simpson *et al.*, 1953b).

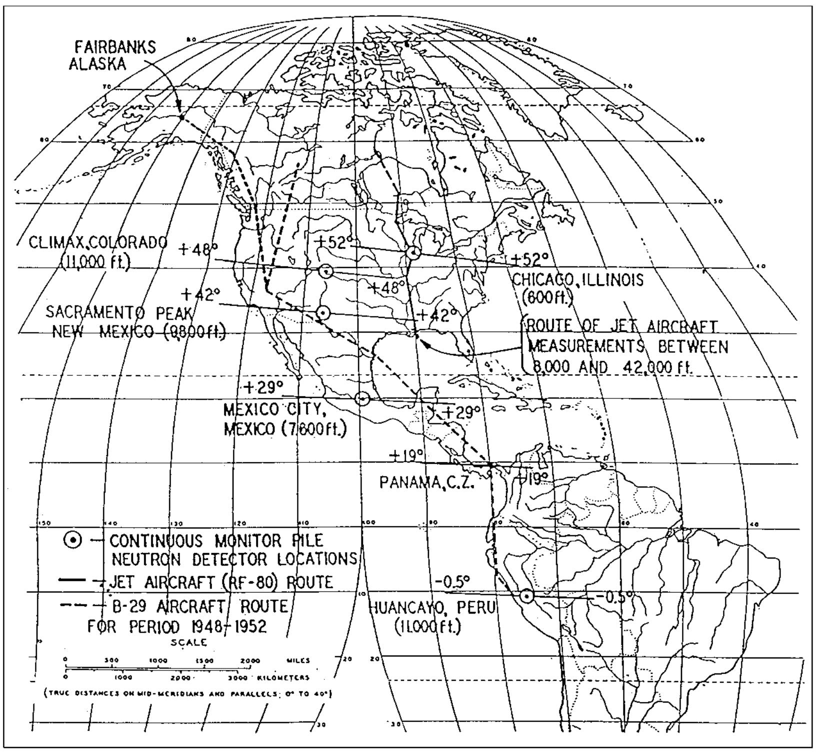


Figure 6. B-29 plane ran course from Fairbanks, Alaska, down to Peru. A jet-plane flew down the middle of the country.

of these low energy cosmic-ray intensity variations was to undertake continuous monitoring of the nucleonic cascade.

At Inyokern in 1948, I was considering the effect of atmospheric production vs. local production of fast neutrons, estimating that the multiplicity of neutron production in elements of atomic weight, A, probably increased as $A^{2/3}$, as would be predicted from nuclear physics theory. This idea led to my conception of a cosmic-ray neutron monitoring system based on measuring the local production of fast neutrons in a high atomic weight target. The instrument would be analogous to a subcritical nuclear reactor in which lead would substitute for uranium as the producer of neutrons, and hydrogenous materials (such as paraffin wax) would substitute for the carbon or heavy water moderator and tamper. Thus the fragmentation of a lead nucleus by an incident high-energy secondary nucleon in the nucleonic cascade of cosmic ray origin would yield a multiplicity of fast neutrons, which would then become thermalized in the surrounding paraffin wax and be detected with high efficiency using $^{10}BF_3$ proportional counters embedded in the 'pile'. With the detection of energetic He^{++} in a proportional counter from slow neutron capture in ^{10}B (Equation 1), the monitor was immune to both the electromagnetic component and external low energy neutron flux variations due to changing local conditions. Finding that I could purchase at the local Navy post exchange an adequate supply of paraffin wax packaged for sale for canning food, I decided to construct a pile inside the B-29 rear cabin utilizing the lead from my meson telescope and BF_3 counters from my existing experiment in the aircraft (Figure 8). We constructed the pile holding the makeshift assembly together for flight with cargo straps secured to the floor boards. It worked, and for me this was the beginning of investigations that led both to my research in cosmic-ray astrophysics and to my researches on the origin of the intensity-time variations.

Aircraft flights with this improvised neutron monitor proved that its dependence on pressure-altitude and latitude above $\sim 40°$ were in agreement with the free-atmosphere dependence of the fast neutron intensity.

We also needed independent evidence that the latitude dependence of our fast neutron density measurements was a true representation in latitude and altitude of the nuclear disintegrations observed as 'star' events in nuclear emulsions. This was achieved by constructing and flying pulse ion chambers (Simpson *et al.*, 1951).

The development of a practical neutron monitor was undertaken in 1948 and 1949 by, for example, studies of neutron moderating geometries (Figure 9) and determining the optimum thickness of paraffin for moderating disintegration product neutrons. Local neutron production as a function of the absorber atomic mass, was investigated for C, Al, Cu, Sn and Pb (later also U) and shown in Figure 10 to confirm the predictions of nuclear theory (Simpson and Uretz, 1953).

These studies led in 1949 to a basic 'standard' pile design, shown in Figures 11 and 12, with an account of its dependence only on barometric pressure (Simpson, 1953; Simpson *et al.*, 1953b). Furthermore, this design could be extended in size to multiply the counting rate from the pile, as shown in Figure 13. The 12 counter

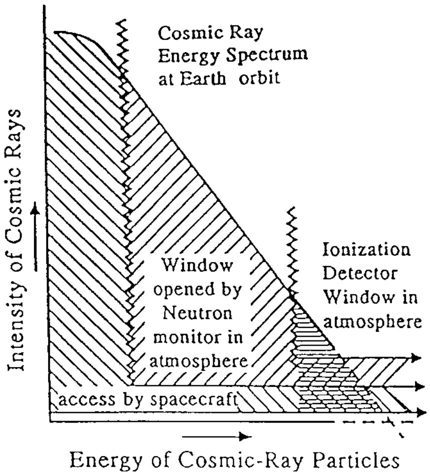


Figure 7. Windows of access to the secondary components inside the atmosphere (shown in Figure 1) are compared to the entire range of energies accessible by spacecraft (Simpson, 1994).

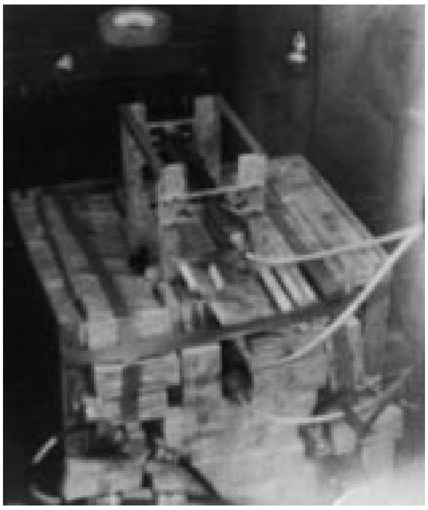


Figure 8. The first neutron pile constructed in the rear cabin of a B-29 aircraft, January-February, 1948 (Simpson, 1985).

configuration became the standard neutron monitor design for Chicago and Climax, Colorado in 1949; later it was the design adopted for the International Geophysical Year (1957–1958) at more than sixty (60) sites world-wide (Simpson, 1958). With pure lead the response time for the 12-counter standard pile was $\sim$150 μs for a stepwise change of intensity at the top of the atmosphere.

From 1951 onward we established continously-operating 12-counter neutron monitors, extending from $\sim 0°$ to 52° geomagnetic latitude – namely, in Huancayo,

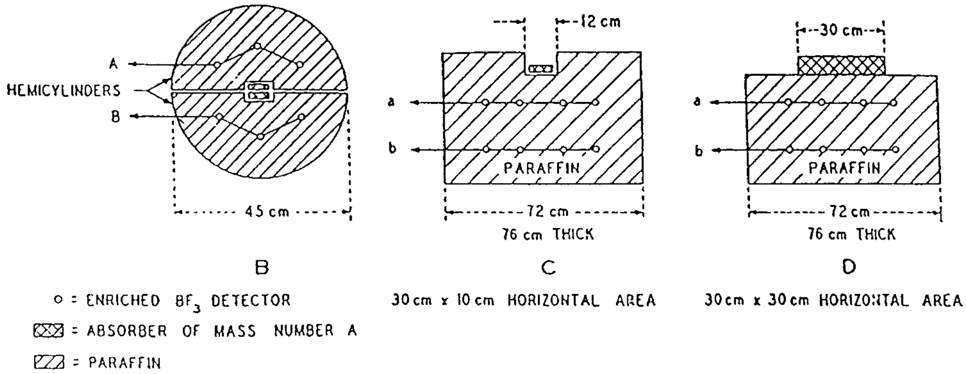


Figure 9. Pile geometries of local neutron producer with paraffin moderator. These geometries were carried by B-29 aircraft from geomagnetic latitude 0° to 65° N. All measurements were obtained in spring and summer months 1948 and 1949 (Simpson and Uretz, 1953).

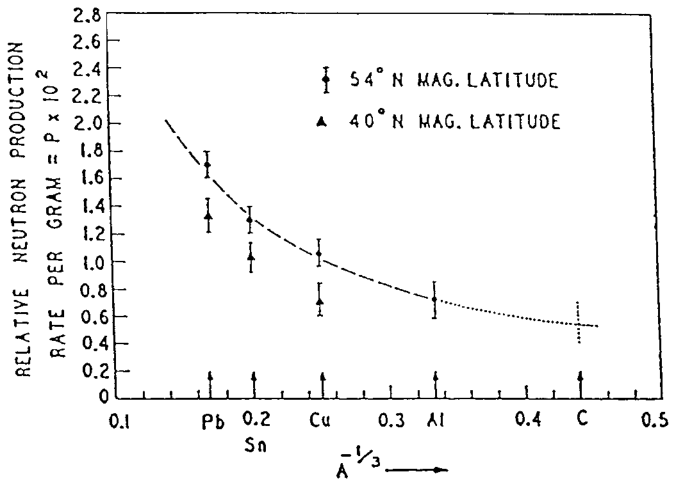


Figure 10. Local neutron production as a function of atomic weight A. The upper curve is for $\lambda = 54°$ and the lower points are for $\lambda = 40°$ (Simpson and Uretz, 1953).

Peru, Mexico City, Sacramento Peak, New Mexico, Climax, Colorado and Chicago (Figure 6).

To relate the observed secondary nucleonic component in intensity to the incoming primary intensity of charge Ze particles, whether at sea level or at high altitude, my graduate student S. B. Treiman and I (Treiman, 1952 Simpson *et al.*, 1953b) developed a specific yield function, S. Thus, the observed counting rate R at atmospheric depth x, geomagnetic latitude λ, particle momentum p,

time t, vertical cutoff magnetic rigidity $\left[\frac{p}{z}\right]$ at λ, and for a differential flux j_z, is

Figure 11. The author with a standard neutron monitor (circa, 1950).

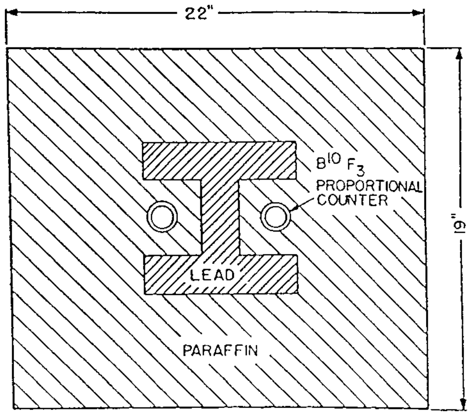


Figure 12. Cross-section view of the ‘basic’ pile used at some of the early observing sites. This geometry may be readily reproduced for comparison with the measurements reported in this paper (Simpson *et al.*, 1953b).

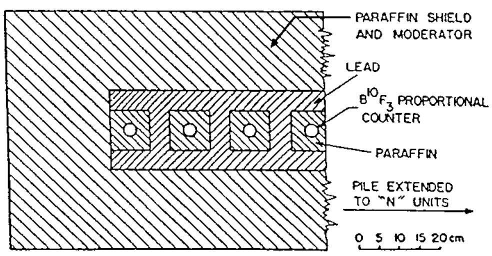


Figure 13. The pile, extended to 12 counters, is used as the detector at Chicago and Climax (11 000 ft.). This pile is composed of 6500-lb lead plus approximately 3000-lb paraffin. Cross-section view (Simpson *et al.*, 1953b) (see Figure 11).

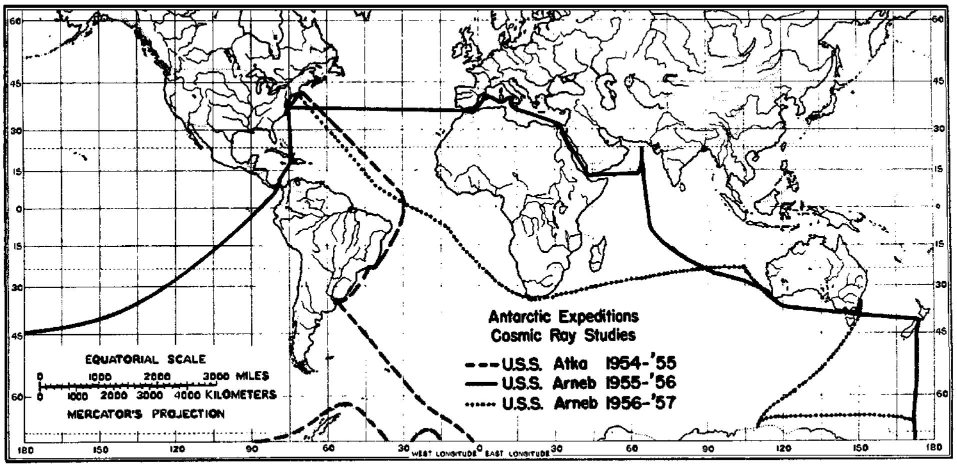


Figure 14. Routes followed by the University of Chicago cosmic-ray Laboratory on its expeditions aboard U.S. naval vessels (Simpson, 1957).

$$R(\lambda, x, t) \;=\; \Sigma_z \int_{\left[\frac{p}{z}\right]}^{\infty} s_z\, j_z \left(\frac{p}{z}, t\right)\, d\left(\frac{p}{z}\right) . \qquad (2)$$

Although we had extensive high-altitude measurements for the determination of the specific yield function, S, over a wide range of geomagnetic cutoffs, a sea level latitude range of S values was lacking.

In order to determine the sea-level latitude dependence of the nucleonic component, we arranged with the U.S. Navy to provide ice breaker ships with laboratories built on their decks to carry neutron monitors under our supervision over the period 1954–1958 towards the South Pole (Figure 14, Simpson, 1957). Canada's National Research Council provided the H.M.S. Labrador to extend our sea-level measurements towards the north polar regions (Rose *et al.*, 1956) with the same neutron monitor.

To establish the minimum intensity of the nucleonic component around the Earth (the cosmic-ray 'equator') we convinced the U.S. Air Force Strategic Air Command to provide aircraft, men and materials for a 90 000 mile expedition around the Earth. To search for the minimum intensity, we made a series of traversals at 12 different longitudes. The route is shown in Figure 15(a) with the data in Figure 15(b) (Katz *et al.*, 1958).

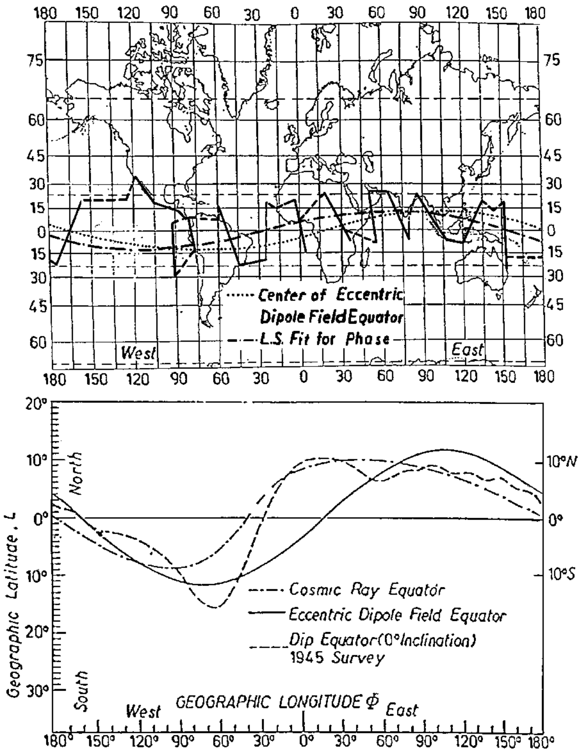


Figure 15. Upper panel: route of aircraft carrying neutron intensity monitor at 18 000 feet pressure altitude. The solid line portions of the route correspond to the latitude curves (Katz *et al.*, 1958). *Lower panel:* a comparison of the cosmic-ray, dipole and dip equators (Katz *et al.*, 1958).

4. The Interplanetary Origin of the Low Energy Cosmic-Ray Intensity Variations

Returning to my early evidence (e.g., Figure 3) that the nucleonic component displayed intensity variations both below and above the knee of the geomagnetic latitude observations, I investigated earlier reports derived from ion chambers and charged particle telescopes. S.E. Forbush, from the late 1930's gave convincing and beautiful evidence of intensity variations derived from his elegant statistical analyses of data obtained using the worldwide distribution of Compton-Bennett Model-C ionization chambers (Compton *et al.*, 1934). This was a program sponsored by the Carnegie Institution of Washington's Department of Terrestrial Magnetism (DTM).

The works of Scott E. Forbush collected by James VanAllen have now appeared in a volume published by the American Geophysical Union (Forbush, 1993). Through the application of rigorous analytical methods, Forbush discovered all the principal cosmic ray intensity variations that could be measured by ionization chambers. He showed that they were correlated with changes in geomagnetic field

Figure 16. Smaller version of neutron detectors (or 'pile') placed in nose of RF-80 jet to measure intensity variations (Simpson, 1953).

intensity, such as occur in geomagnetic storms. Perhaps his most widely known correlation was a rapid decrease of cosmic-ray intensity correlated with a worldwide change in geomagnetic field intensity. When I became familiar with this effect, I called it a Forbush-type decrease, a term widely used today.

The mechanism proposed at that time to account for this Forbush-type decrease was based on increases in the worldwide magnetic field intensity arising from an enhanced equatorial ring current produced by solar ion streams. For incident cosmic-ray protons the effect was equivalent to a temporary increase in the Earth's dipole magnetic moment.

With my neutron monitors in continuous operation by 1950–1951 and with a miniature neutron monitor pile mounted in the nose compartment of a U.S. RF80 jet (Figure 16) stationed near Chicago in 1951 (Simpson, 1953), I could command latitude flights at times of large ground level intensity changes.

To investigate the origin of both the Forbush decrease and the 27-day recurring intensity variations, I carried out latitude measurements extending above and below the knee in order to test the prevailing view that the intensity variations were geophysical in origin. If the cosmic-ray intensity variations were due to an enhancement of the geomagnetic cutoff for cosmic-rays, the latitude intensity curves for the nucleonic component would shift, as shown in the sketch Figure 17, whereas if the origin was a change in cosmic-ray intensity in the interplanetary medium, the latitude curves would display intensity variations above and below the knee.

The experimental results I obtained in 1949–1951 were clear for both the Forbush-type decreases and the ~27-day intensity decreases, as shown by the example in Figure 18. I concluded that the origin of the intensity changes was beyond the range of the geomagnetic field. Since the cosmic-ray intensity from the galaxy must be constant over long periods of time, the experimental results

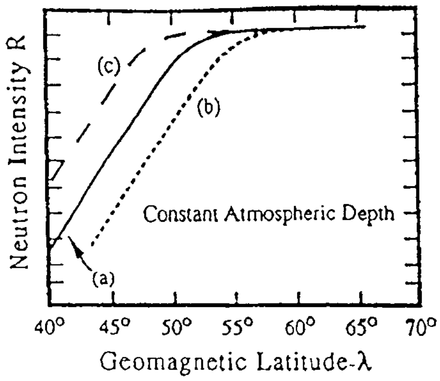


Figure 17. The predicted behavior of neutron intensity as a function of latitude based upon the assumption that the primary cosmic-radiation intensity variations is produced by a geomagnetic field variation.

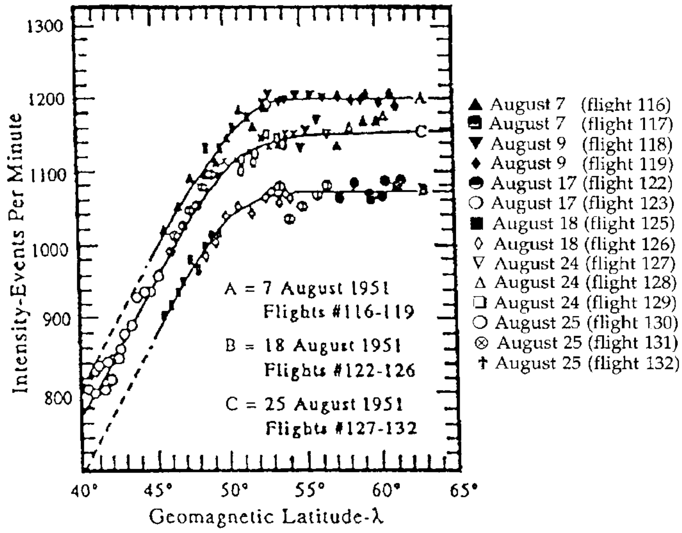


Figure 18. The neutron intensity data used to establish the latitude curves for August 7, 18 and 25, 1951, are shown. The smooth curves (with dashed lines for extra- polations) are used for analysis. The curves are based upon several air- craft flights listed at the right-hand side of the figure (standard devia- tions are approximately the size of the flight identification symbols). (Adapted from Meyer and Simpson, 1955.)

pointed to an origin of the Forbush decreases and ~27-day recurring variations in the intervening interplanetary medium and with control by the Sun. By 1952 my investigations led to what I called solar modulation.

4.1. THE ~11 YEAR SOLAR ACTIVITY CYCLE

For subsequent latitudes flights extending into the 1994 solar minimum, Peter Meyer had become a collaborator. We found (Meyer and Simpson, 1955) that not

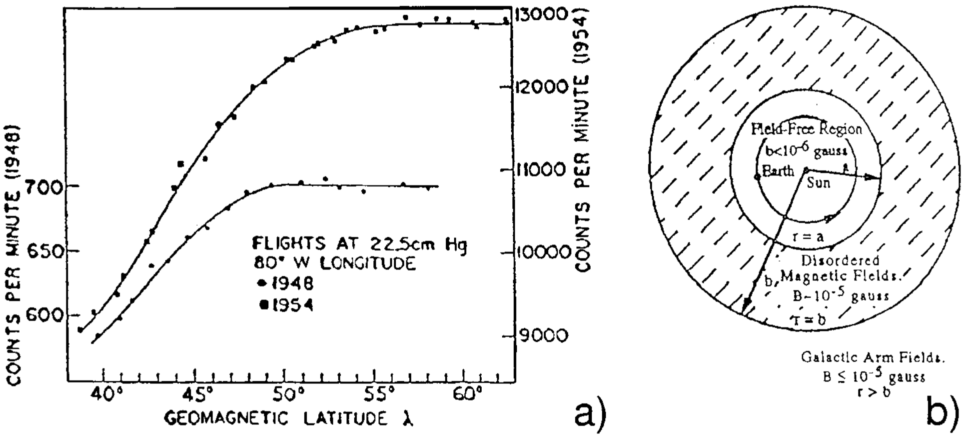


Figure 19. a): The nucleonic component latitude curves for 1948 and 1954 at 80° west longitude 310 g/cm^2 atmospheric depth. The data for the 1954 flights are for November 13, 14, and 15, 1954. *b):* The primitive heliospheric model. Cross section of the model for the inner solar system at the time of the solar flare of February 23, 1956. The inner volume $r = a$ represents a cavity 'free' of magnetic fields ($B_{\mathrm{r.m.s.}} < 10^{-6}$ G). The barrier of thickness $b - a$ represents the shell-like region through which the cosmic-rays diffuse. (From Meyer *et al.*, 1956).

only the integral intensity had increases by ~13% between 1948 and 1954, but that the knee shifted to higher latitude, as shown in Figure 19(a). Thus we learned that as the level of the ~11 year solar cycle declined to solar minimum over this 4-year period, an additional flux of low-energy primary cosmic-ray particles had access to the top of the atmosphere, changing the integral magnetic rigidity spectrum of the primary cosmic-rays.

About this time in 1954, Forbush (1954, 1958) independently published his important ion chamber measurements from 1937–1952, showing that the approximately 4% intensity variation be observed over each 11 year solar cycle was 'negatively correlated with sunspot number' (Forbush, 1954, p. 183). Forbush (1954, p. 184) noted that the long-term ion chamber intensity variations 'are not ascribable to transient decreases accompanying some magnetic storms,' but he had no other comment on the origin of the negative correlation. In his editorial foreword to the works of Forbush (1993, p. viii) James Van Allen noted:

"In none of his papers did he propose that either a Forbush decrease or the 11-year intensity cycle was caused by the interplanetary medium; but later with characteristic modesty, he welcomed and embraced this line of interpretation as established by others."

Simpson *et al.* (1955, p. 1522) concluded that his negative correlation and our investigations, carried out between 1948 and 1954, provided further evidence that the mechanism accounting for our findings was a property of long-term solar system modulation.

4.2. The 27-day Recurrent Modulation

What was the origin of the ≈ 27 day recurring intensity variations? By analyzing both neutron and Forbush's ionization chamber data Meyer and I found that its amplitude was closely related in time to the minima and maxima of the ≈ 11 year solar activity and concluded that solar active regions controlled the extraterrestrial origin of the 27-day cosmic-ray primary intensity variations (Meyer and Simpson, 1955). My search for the region on the Sun responsible for these recurring intensity variations after my only partially successful attempts at correlations with intense recurring coronal green line emission regions (Simpson *et al.*, 1953a), focused on the work by H.W. Babcock (1953). He had developed a method for making extensive solar magnetic field maps, based on the Zeeman effect, which resulted in a series of composite 'snap shots' of the polarity distribution of the solar magnetic fields above the photosphere. This led to our joint paper showing the correlation of recurring unipolar magnetic field regions (UM) with the 27-day recurring cosmic-ray intensity modulation (Simpson *et al.*, 1955, p. 1405). This investigation may have been the first evidence for a coronal hole. The history of recurrent modulation has been reviewed recently (Simpson, 1998).

4.3. Discovery of a Dynamical Heliosphere

With our neutron monitor 'geomagnetic spectrometer' fully operational by 1951, and with a balloon-borne instrument that we could launch on short notice from the Stagg Sports Field of the University of Chicago, I was ready for the next major solar flare. We had included special instrumentation in the Chicago and Climax neutron monitors that could detect a rapid, large-intensity increase and trigger the University telephone operator to call me in Chicago. E.N. Parker joined our group in 1955.

We had to wait until 1956 when the alarms at Climax and Chicago were triggered by the February 23, 1956, solar flare (Meyer *et al.*, 1956; Simpson, 1985). We converged on Stagg Field within hours to launch a balloon to measure the absorption of the solar flare particles generating the nucleonic cascade in the atmosphere. This solar flare event was recorded by our neutron monitor network, including the monitor onboard the USS Arneb, then in Wellington Harbor, New Zealand (Figure 14). The solar flare proton energy spectrum extended beyond ≈ 20 GeV. (Thirty-three years were to elapse before another flare with particles of comparable energy was observed.) The sudden and short burst of relativistic nucleons had revealed regions beyond the orbit of Earth through which they could only slowly escape to the interstellar medium. In our analysis of this solar flare event (Meyer *et al.*, 1956) we showed that the solar flare accelerated nuclei were scattered by and diffused through a continuous barrier region of irregular magnetic fields beyond the orbit of Earth before reaching interstellar space. In order to explain these observations we proposed a model with this barrier region extending beyond the orbit of Earth to about 5 AU in radius totally enclosing the solar system (Figure 19(b)), with a cavity in the inner solar system. Although a static cavity region was proposed in a theoretical model by Davis (1955), our investigation provided the first experimental evidence for a dynamical heliosphere. The spacecraft Pioneer-10 and Voyager-1 are now beyond 70 AU and are still in the heliosphere. How naive we were in 1956!

It was becoming clear that the interplanetary magnetic field, invoked to account for the February 23, 1956, solar particle propagation, must also be central to the explanation of how galactic cosmic rays are modulated over the long term. The barrier model of Davis (1955) would not work since it was static and would not prevent the full galactic flux from entering the solar cavity within a short time. Morrison (1956) and Parker (1956) had suggested outward moving magnetic clouds to account for the modulation, but as summarized by Parker (1963) there were serious difficulties with these suggestions. Parker went on to develop the quantitative theory for coronal expansion and extension of the solar wind into interplanetary space carrying solar magnetic fields which formed an archimedian-type spiral field near the equator (Parker, 1963). Parker published important accounts of a basic model for solar modulation that embodied the principles underlying all modulation theories today.

5. Examples of Applications Derived from the Uses of the Nucleonic Cascade and Neutron Monitors

5.1. Radiocarbon Dating

Libby (1946, 1955) pointed out that, since neutrons would be produced by the cosmic radiation and slow down in the atmosphere, the reaction

$$^{14}\mathrm{N} + n \rightarrow ^{14}\mathrm{C} + ^{1}\mathrm{H} \quad (3)$$

would be an important source of ^{14}C. With a half life of $\sim$ 5630 years, the ^{14}C in the atmosphere would rapidly form radioactive $^{14}CO_2$. Since plants live off CO_2 all plants will be radioactive. Thus, it becomes possible to use ^{14}C to date the products of plants, trees, etc., since $^{14}CO_2$ intake ceases at the death of the plant. Comparing samples of known age (e.g., Sesostris [1800 B.C.] with ^{14}C dating based on the available high latitude neutron measurements in 1939–1946, see Introduction), Libby found large discrepancies. However, after correcting for the world-wide neutron latitude dependencies, satisfactory agreement was achieved in 1948 (see Libby, 1955; Simpson, 1994).

5.2. World-wide Networks of Neutron Monitors

Through the period 1951–1953 our neutron monitors extended from 0° to $\sim$ 52° geomagnetic latitude but only over a narrow longitude range (Figure 6), as I reported at the 1953 International cosmic-ray Conference. There was widespread

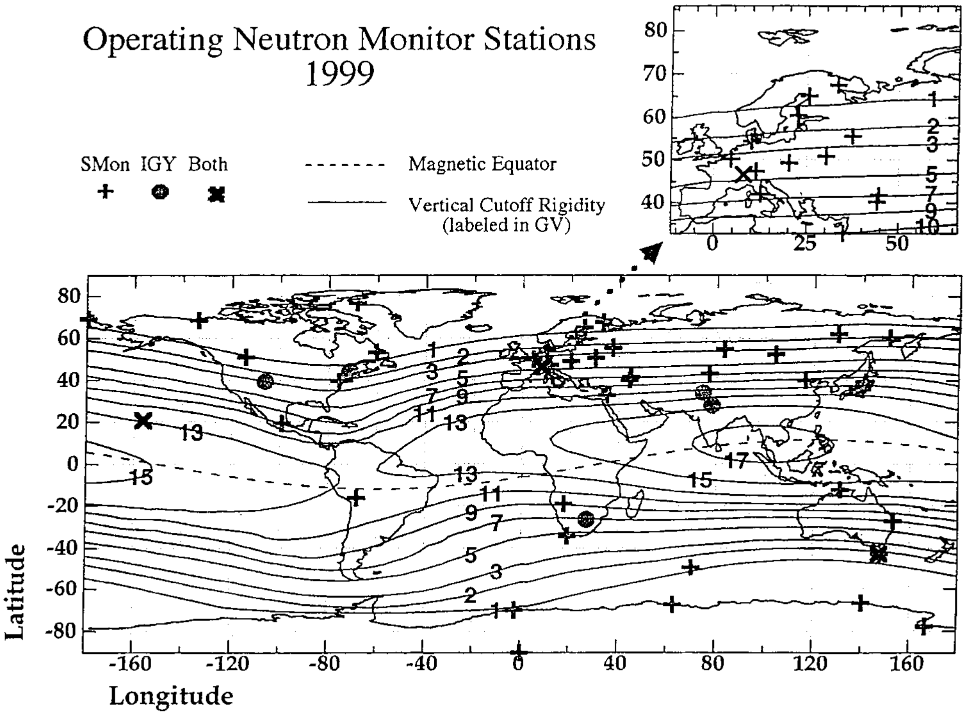


Figure 20. A map of the world with the locations of all fifty-three presently operating neutron monitor stations. Locations are labeled as to whether they contain standard International Geophysical Year (IGY) stations, supermonitor (SMon) stations, or both IGY and SMon stations. The European area is shown in a blowup insert figure in the upper right corner.

interest in the neutron monitor concept. Immediately, F.G. Houtermans insisted that I visit him in Bern to select a site on the Jungfraujoch. This turned out to be the beginning for a worldwide array of stations by many nations (see Figure 20). During the International Geophysical Year (1957–1958) the standard neutron monitor design – now called the IGY neutron monitor – was installed at more than 60 sites by the 68 nations participating in the IGY.

It was not until 1964 that a new neutron monitor design was developed (H. Carmichael, 1964) to greatly increase the neutron counting rates. The new design is now called the super-monitor. In 1998 more than 52 cosmic-ray neutron monitor stations are in continuous operation throughout the world to support a wide range of research. For example, solar flare acceleration of nucleons over the energy range $\sim$1 to $>$20 GeV per nucleon can be investigated at any time. This is an energy range extending far beyond the range of spacecraft experiments.

Figure 21 illustrates how various spacecraft measurements may be monitored simultaneously at higher energies, such as by the Climax neutron monitor and the series of IMP instruments over a complete solar magnetic cycle. It is unlikely that

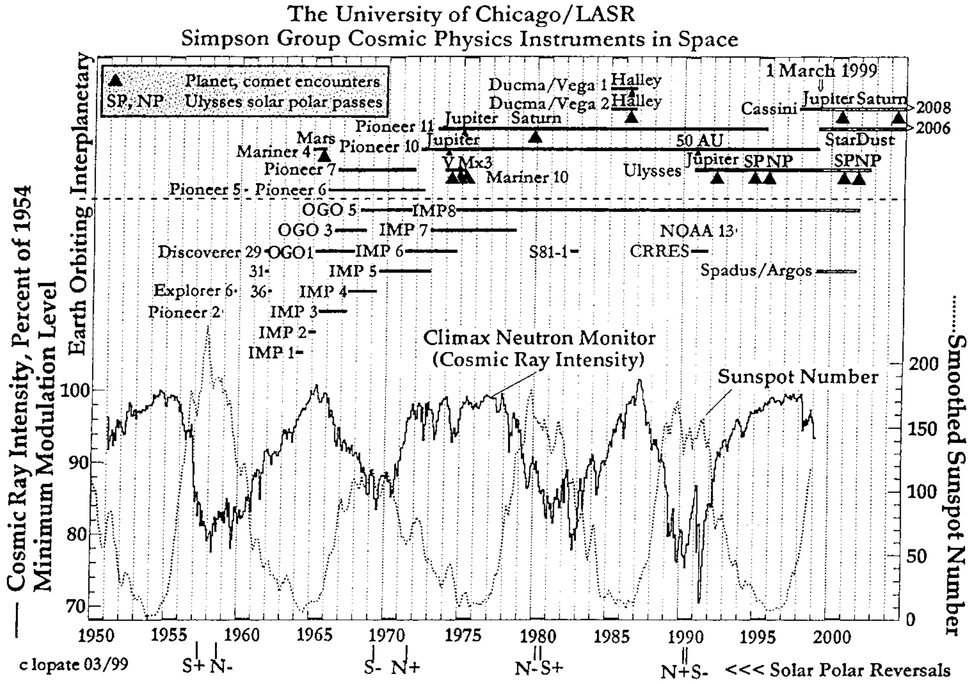


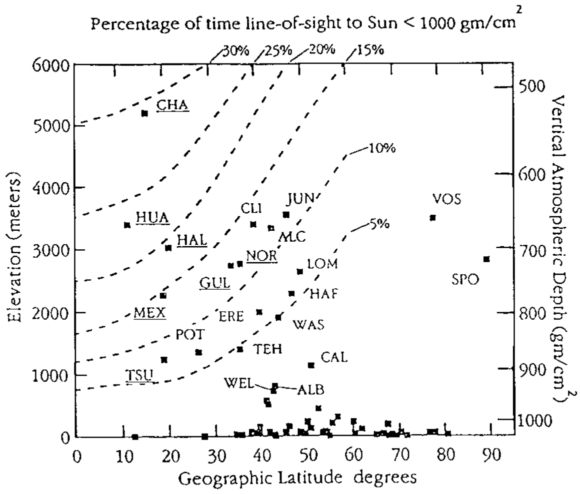
Figure 21. The lower graph contains Bartels solar rotation averages of the Climax Colorado IGY neutron monitor rate (as a percentage of the 1954 minimum solar modulation level) plotted with a five-month running average of the sunspot number. The upper part of the figure contains the space missions of the Simpson group at the University of Chicago / Enrico Fermi Institute. Solid bars indicate times over which space missions have flown. Open bars indicate the projected lifetimes of ongoing space missions.

there will be continuous monitor in spacecraft in the energy range to $\sim$20 GeV in the foreseeable future.

As a third example, we note that the first detection through the atmosphere of solar flare neutrons by the Swiss group (Chupp *et al.*, 1987; Debrunner *et al.*, 1983) has opened up research on solar flare acceleration in the upper versus the lower corona. Pyle (1993) has reviewed the sensitivity of neutron monitors for solar flare neutron detection in stations of the world-wide network showing the advantage of a high geomagnetic cut-off and high altitude (Figure 22). These are rare events that require continuous monitoring by the world-wide network.

6. Concluding Remarks

The opening of the Space Age in 1957 provided the opportunity to directly study the dynamical phenomena that, in earlier years, could only be deduced indirectly due to the intervention of Earth’s atmosphere. The heliosphere has become our astrophysics laboratory for the study of, for example, galactic cosmic-ray modu-



ALB	S	Alma-Ata B	HAF	S	Hafelekar	WAS	I	Mt. Washington
ALC	S	Alma-Ata C	HAL	2	Haleakala	WEL	S	Mt. Wellington
CAL	S	Calgary	HUA	I	Huancayo	POT	I	Potchefstroom
CHA	S	Chacaltaya	JUN	2	Jungfraujoch	SPO	S	South Pole
CLI	I	Climax	LOM	S	Lomnicky Stit	TEH	I	Tehran
ERE	S	Erevan	MEX	S	Mexico City	TSU	I	Tsumeb
GUL	I	Gulmarg	NOR	S	Mt. Norikura	VOS	S	Vostok

S = NM-64 (Supermonitor) I = IGY (Standard Monitor) 2 = Both
Underline = Vertical Cutoff Rigidity > 8 GV

Figure 22. Summary of several parameters relevant to the detection of solar neutrons for existing neutron monitor stations throughout the world. The labeled dashed contours indicate the percentage of time that the line-of-site air mass between the Sun and the station is less than 1000 g cm^{-2}, a function of geographic latitude and altitude/pressure (Pyle, 1993).

lation, charged particle acceleration and phenomena dominated by the solar wind. Nevertheless, it is surprising how many phenomena were first identified by investigations requiring neutron monitor instrumentation. I find it even more surprising that about fifty years later after its development, the neutron monitor continues to be required for many investigations and that new scientific applications for it lie ahead. This will be one of the themes of the ‘cosmic-rays and Earth’ Workshop.

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