New Knowledge of the Extra-Atmospheric Radiation Field

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WHEN RADIATION hazards in extra-atmospheric flight are discussed, one usually thinks of exposures of brief duration and in terms of rare and extraordinary events not subjected to the stringent standards of other fields of science and industry where workers come in contact with ionizing radiation. Whether this is still a realistic attitude in view of recent developments seems questionable.

It is too early to make a specific prediction at what time in the future an observation vehicle carrying one or two men will circle the globe, but no one is likely to doubt that this will come true soon. If the tremendous

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cost of launching such a vehicle and putting it into orbit is considered, whereas there are no expenses for propulsion fuel for keeping the vehicle in orbit for any desired length of time, it is self-evident that the on-duty time of the men in such a ship will have to be extended to the utmost limit which human endurance and the technicalities of oxygen and food supply permit. Frequent relief of the crew in a future global reconnaissance vehicle will be costly. Those crew members, then, will be exposed to the extra-atmospheric radiation field for longer periods, maybe of days, or even of weeks. No one would advocate applying common radiation safety standards to these men. It should be generally agreed, however, that the amount and nature of the radiation exposure must be accurately determined and that such exposure is not just called a calculated risk, but is calculated properly.

The problem of a quantitative appraisal of the radiation effects on man in the extra-atmospheric region is far from being satisfactorily solved. Quite aside from gaps in the basic radiobiologic understanding of the mode of action of heavy nuclei or large disintegration stars on living matter, available information is even incomplete with regard to purely physical parameters, such as the intensity and composition of the ionizing radiation outside the atmosphere. New experimental data collected in recent years have brought about considerable changes in the basic concepts of the origin and the mechanism of propagation of cosmic radiation as well as of additional powerful sources of penetrating radiation. Inevitably, these new findings also affect the implications concerning the radiation dosages involved in extra-atmospheric flight.

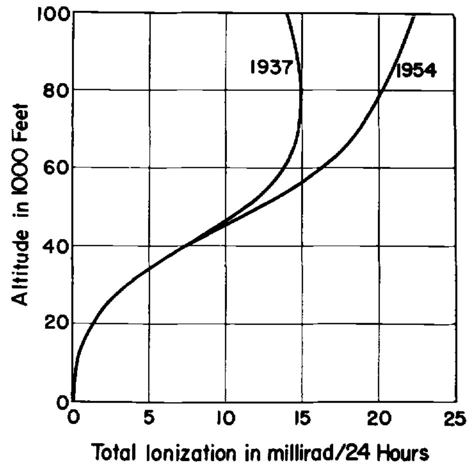

Fig. 1. Altitude profile of the total ionization in a year of high (1937) and low (1954) solar activity, based on data of H. V. Neher.[3] Note limitation of change to region of high altitude.

COSMIC RAY INTENSITY VARIATIONS CORRELATED TO THE SOLAR CYCLE

A phenomenon of great significance is the periodic change of the radiation intensity in correlation with the eleven-year cycle of solar activity. This effect is limited to the components of low penetrating power of the cosmic ray beam. Therefore, it is felt only at extreme altitudes and has escaped detection for a long time. Neher[3] has presented a set of comprehensive data on the altitude profile of the total ionization collected during a period of more than twenty years. Figure 1 shows two curves compiled from Neher's data depicting the total ionization as a function of altitude in 1937, a year of high solar activity, and in 1954 during which the sun was at its lowest ebb in twenty-two years. It is clearly seen that the total ionization at the top of the atmosphere in 1937 exhibits a pronounced transition effect with a maximum intensity at 78,000 feet. At low activity, in 1954, no transition effect exists. The total ionization increases monotonically through the full altitude range of the atmosphere and is at extreme altitudes substantially larger than in 1937.

A tentative explanation for the effect has been suggested among others by Forbush[2] attributing the phenomenon to a solar magnetic field. At times of high solar activity this field is strong and exceeds at a certain latitude the shielding power of the geomagnetic field, thereby preventing low-energy cosmic ray particles from reaching the earth in the region from the critical latitude to the pole. Since these low-energy particles have limited penetrating power, only the intensity at extreme altitude is affected (Fig. 1).

The importance of these findings for the exposure hazard rests upon the fact that low-energy particles are the main contributors to the biological effect because of their high rate of energy loss (REL). For a quantitative appraisal it would be necessary to know the relative shares of the various types of nuclei in the total ionization. Neher's measurements do not contain clues in this respect. However, if the hypothesis of a heliomagnetic origin of the phenomenon is accepted, the spectral composition of the additional intensity can be extrapolated simply by extending the normal energy spectrum below the cutoff energy. This extrapolation is shown for the lightest (CNO) and the heaviest (Fe) component of the heavy spectrum in Figure 2. Plotted is the differential range spectrum, broken down in the two fractions of particles terminating in nuclear collisions and particles terminating in thindowns. Since the REL reaches by far its highest values in the thindown events, the latter fraction represents the biologically significant part of the total beam. It is seen, then, that the alternative of a heliomagnetic cutoff being present or absent makes a profound difference in the dosage, a difference which considerably exceeds the corresponding difference in the total ionization. This circumstance emphasizes the importance of these relationships for the exposure hazard and stresses the need for a detailed experimental verification of the speculative interpretation presented in Figure 2.

COSMIC RAY EMISSION IN SOLAR FLARES

Solar influences are not limited to indirect, modulating effects on cosmic ray intensity, described in the preceding section. Evidence is accumulating that the sun itself is a powerful source of cosmic radiation. This has been conjectured during several large flares of earlier solar maxima, but has become abundantly clear during the giant flare of February 23, 1956. The radiobiologic implication of the latter event has been described in detail.[5] Although the extra-atmospheric tissue dosage during, and for some hours immediately following, a large flare is considerable, reaching the order of magnitude of several rad-units, such flares are rare events and occur infrequently during an entire maximum of solar activity which extends over several years.

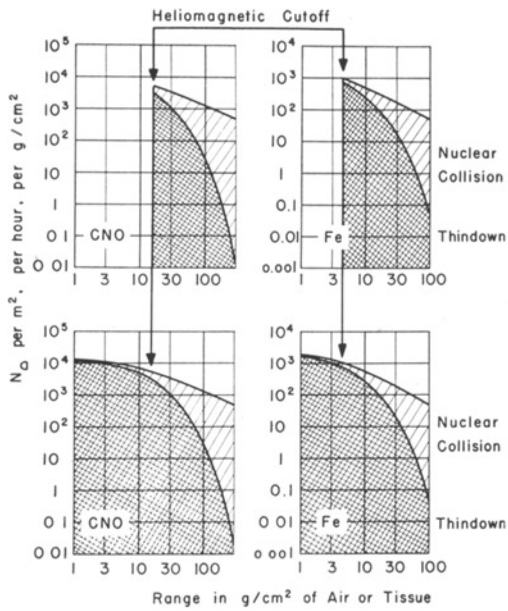

Fig. 2. Differential range spectra for CNO and Fe nuclei with (upper pair) and without (lower) heliomagnetic cutoff. Note large increase of thindown fraction in the low range section.

IONIZATION DOSAGE INFLIGHT THROUGH AURORAL DISPLAYS

A phenomenon of a much more real and practical importance for space flight is the radiation field from x- and beta rays that seems to exist in auroral displays. Rockoon measurements of Meredith, Gottlieb and Van Allen[4] and of Van Allen,[6] and balloon measurements of Winckler and Peterson[7] have furnished evidence in this respect. While the data collected so far permit only an informed guess with regard to the tissue ionization dosages involved, they establish rigorously one basic fact. For the energy spectrum of the charged particles in auroral displays, no geomagnetic cutoff exists as it is observed in the ordinary cosmic ray beam outside auroral regions. An explanation for this fact is not readily available. It has been conjectured that moving clouds of ionized gases, originating from the sun, are responsible. These clouds produce and carry their own magnetic fields which interfere with the earth's field and produce field configurations within the cloud that greatly differ from the normal pattern in the interplanetary region.[1]

Of special interest is the interpretation of the experimental data in terms of the ionization dosages that prevail in auroral displays. The data of Winckler and Peterson[7] have been obtained in a skyhook balloon flight on July 1, 1957. The balloon was launched at about 1.30 U.T. (Universal Time). The instrumentation consisted of a Geiger counter and an integrating pulse ionization chamber, both set to record ionizing particles. Simultaneously with the onset of a brilliant auroral display, well after the balloon had reached level altitude, both instruments recorded and telemetered a considerable increase of "cosmic" ray intensity. The comparative evaluation of the readings of the two different types of instruments permits a direct inference as to the ionization dosage. It was 5 millirad per hour. One has to realize that this is the intensity at 109,000 feet altitude corresponding to an atmospheric depth of 8 g/cm^2, that is, in a region far below the aurora itself and, therefore, far below the center of emission of the radiation. Because the additional radiation is of moderate penetrating power resembling medium hard x-rays, considerably greater intensities must have prevailed in the region of the aurora itself, as the radiation reaching the instruments has been attenuated by 8 g/cm^2 of air between the balloon and the aurora. It stands to reason that any extrapolation as to this intensity at the point of origin is subjected to a vast uncertainty as long as the spectral composition of the radiation and the spatial extension of the emitting "cloud" of ionized gases is not known.

Somewhat narrower limits for a first estimate of the intensities of ionizing radiation involved in the phenomenon under discussion can be drawn from the experimental data of the Iowa group under Van Allen.[6] The rockoon vehicles of these investigators actually reached auroral altitudes and therefore can be assumed to have measured the intensity at the place of origin. Figure 3 summarizes the data of Van Allen and tries to describe the salient point. As has been mentioned above, one should expect a lowering and leveling off of the geomagnetic cutoff energy for charged particles reaching the earth as one proceeds to higher latitudes. Correspondingly, the intensity should increase, as more low energy particles are admitted and should finally level off in the region where the heliomagnetic cutoff takes over. The upper graph of Figure 3 shows this relationship as it affects the minimum momentum of arrival as a function of latitude. The center graph shows a survey of the intensities recorded in the rockoon flights of Van Allen. Finally, the lower graph shows the frequency distribution of auroral displays as a function of latitude. The strong correlation between the occurrence of abnormal "cosmic" ray intensity and the frequency of aurorae is striking. The tentative explanation, then, is that the phenomenon is connected with auroral activity.

The measurements of Van Allen even permit a first estimate of the penetrating power of the new radiation, since a multiple counter arrangement was used with counter tubes placed under various thicknesses of filter material. The recordings indicate that the additional intensity is produced by x-rays of 10 to 100 keV energy. The estimated upper limit of the intensity is 10^5 photons/cm^2 sec. This leads to a dosage of the order of magnitude of 500 millirad per hour.

That is 100 times greater intensity than the one measured by the University of Minnesota team at 109,000 feet altitude mentioned above. Considering the absorber thickness of about 8 g/cm^2 of air between source and monitor in the latter case and, furthermore, the penetrating power of the radiation as estimated from Van Allen's data, one is led to the assumption that the intensity at the place of origin in the aurora itself on July 1, 1957, was considerably higher than 500 millirad per hour. This conclusion is in line with the fact that the display on July 1 was of exceptionally high intensity as judged by the brilliance of its visible appearance.

The measurements of the Iowa and Minneapolis cosmic ray teams on auroral x-rays have very important implications for the problem of radiation hazards in extra-atmospheric flight. We face the fact that in a certain latitude belt of the ionosphere, local conditions develop and vanish irregularly giving rise to a soft ionizing radiation of intensities of the order of magnitude of 10 full rad per 24 hours and exceeding the intensity of the normal cosmic radiation by a factor of at least 1000. This may sound somewhat alarming to the space travel enthusiast. However, as far as the rather incomplete data permit conclusions at all, they seem not to indicate that prohibitive conditions exist with regard to human travel in the ionosphere.

There are two fortunate circumstances that very effectively limit the actually absorbed dose in an exposed human body. One is the limited penetrating power of the auroral x-rays, as indicated by Van Allen's measurements. Already a few millimeters of an ordinary Alclad hull will produce a substantial attenuation. In this connection, it is of interest to realize the

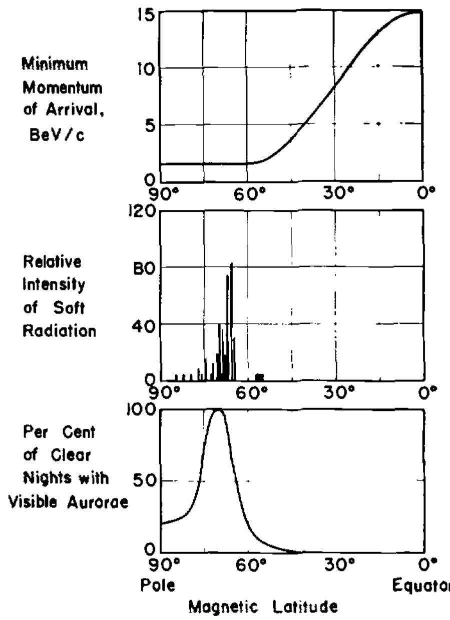

Fig. 3. Top: Minimum momentum of arrival for charged cosmic ray primaries as a function of latitude. Center: Intensity of soft radiation as a function of latitude as recorded by J. A. Van Allen in rocket flights through aurorae. Bottom: Frequency of aurorae as a function of latitude based on data compiled by E. H. Vestine. Note strong correlation of enhanced cosmic ray intensity due to soft radiation in the auroral region.

entirely different laws that govern the absorption of auroral x-rays and of cosmic ray heavy nuclei. Figure 4 presents typical absorption curves for both radiations. Contrary to heavy nuclei, x-rays of the medium hard type as encountered in aurorae are very efficiently shielded already by a thin aluminum sheet. An Alclad hull of 1 millimeter corresponds to about 0.22

grams/cm². It is seen that this reduces the intensity to about 15 per cent of the entrance value. It is also of interest to notice that organic matter, due to its lower mean atomic number, is a less effective absorber on an equal weight basis than aluminum for x-rays, whereas for heavy nuclei the reverse proposition holds.

It follows from these relationships that the body of a human being in a vehicle travelling through an auroral display is already afforded effective protection by the hull of the ship and by clothing. It will depend on more detailed data on the energy spectrum and the time integral of auroral x-rays whether additional shielding will be necessary at all.

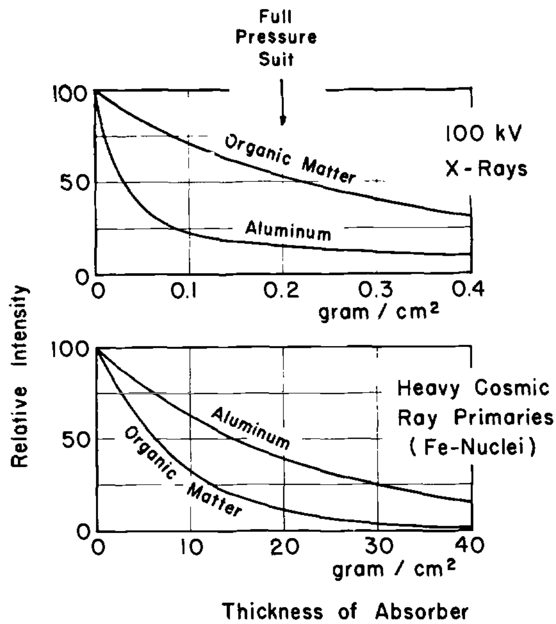

Fig. 4. Attenuation of 100 KV x-rays (top) and heavy cosmic ray primaries (bottom) in organic matter and aluminum. Note greatly different abscissa scales and reversed relative absorptive power of two materials for the two types of radiation.

Another factor that alleviates the exposure hazard lies in the latitude limitation of the phenomenon. If we think again in terms of an earth-circling reconnaissance vehicle, in which very likely the longest on-duty times of men will occur, we immediately see that the vehicle will always spend only a fraction of its circling time in the radiation infested region. How large this fraction will be, depends on the angle between the orbit and the equator. Figure 5 shows the relationship in exact detail. It is seen that the exposure never quite reaches one-third of the full dose.

Much less reassuring are the more speculative aspects concerning the radiation exposure in the regions beyond the ionosphere. The measurements of Van Allen and Winckler reveal the existing complete lack of any specific knowledge as to the fundamental conditions prevailing in these regions. Obviously, the classic concept of geomagnetic shielding of low-energy charged particles, as it is observed in the cosmic ray beam, is not applicable to solar electrons traveling in ionized clouds. Equally obvious is that the current densities and kinetic energies of these electron beams have been underestimated by several orders of magnitude. Indeed, the problems of solar influences on the interplanetary radiation field present themselves as new and fascinating—an unknown territory. It might well be that, as space exploration progresses, the cosmic ray phenomena as we know them today will fall back to second or third place in radiobiologic significance.

SUMMARY

As human flight outside the atmosphere in free inertial orbits is a possibility of the near future, extended exposures to the extra-atmospheric radiation field will become reality. Under these circumstances, the radiobiologic assessment of this exposure appears of immediate practical importance. Unfortunately, this task presents itself at a moment when new experimental data introduce considerable uncertainties in the existing concepts of the intensity and composition of ionizing radiation outside the atmosphere. Three phenomena are of special interest in this respect.

1. The itensity of the primary cosmic radiation exhibits considerable changes in correlation with the solar cycle. Because these changes pertain to the low-energy part of the spectrum, they are felt only at the top of, and outside, the atmosphere and only at high latitudes. For the same reason, they pertain to the biologically most effective region of the spectrum, as low-energy particles have a high rate of energy loss. Quantitative data on the participation of heavy nuclei in this phenomenon are not available.

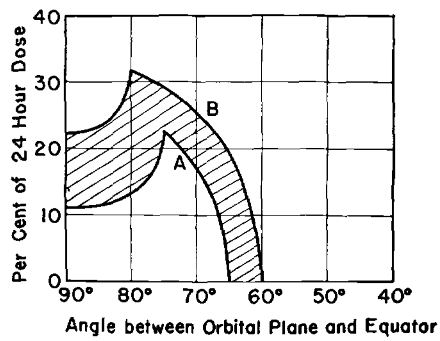

Fig. 5. Fraction of auroral dose for an earth circling satellite as a function of orbit inclination. The radiation infested region A is assumed between 65° and 75° latitude, and B between 60° and 80°.

2. During large solar flares, the extra-atmospheric cosmic ray intensity increases by a factor of several thousands. Here again, the low-energy section is mainly affected.

3. A new soft radiation, presumably a mixture of solar beta rays and locally produced x-rays of 10 to 100 kV energy, has been discovered in auroral regions. The dosage reaches levels of as high as 0.5 r per hour. Yet the limited penetrating power makes shielding feasible with respect to weight requirements. Further alleviating the exposure hazard is the limitation in time and location.

General conclusions as to the configuration and intensity of the radiation field outside the atmosphere seem less possible than ever in the light of the new experimental data. Extrapolations relied upon so far can be expected to undergo revision in many important instances as the exploration of the radiation field in space progresses.

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