EXPERIMENTAL DETERMINATION OF COSMIC-RAY CHARGED PARTICLE INTENSITY PROFILES IN THE ATMOSPHERE

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Absolute cosmic-ray free air ionization and charged particle fluxes and dose rates throughout the atmosphere have been measured on a series of balloon flights that commenced in 1968. Argon-filled ionization chambers equipped with solid-state electrometers, with different gas pressures and steel wall thicknesses, and a pair of aluminum-wall GM counters have provided the basic data, which are supplemented by measurements with air-filled and tissue equivalent ionization chambers and a scintillation spectrometer. Detailed laboratory experiments together with analyses of the theoretical aspects of the detector responses to cosmic radiation indicate that these profiles can be determined to an overall accuracy of ±5 percent.

Data from various balloon flights at 53°N and 42°N geomagnetic latitude provide ionization profiles consistent with our earlier results in the lower atmosphere, but 20 percent lower than comparable data obtained by the California Institute of Technology. No explanation has yet been found for this discrepancy, although a quantitatively similar one was previously noted by the University of Minnesota group. Our results indicate a total charged-particle free-air ionization (dose rate) at 53°N latitude of 6.3 I (9.5 μrad/hr), 114 I (170 μrad/hr), and 290 I (436 μrad/hr) at 10,000, 35,000, and 65,000 ft., respectively. These data are approximately minimum values for the 11 year solar activity cycle.

The ionization and flux data are compared with the analytical calculations of O'Brien, with generally satisfactory agreement between theory and experiment.

I. INTRODUCTION

Many measurements of total ionization and omnidirectional particle flux of cosmic-ray secondaries in the atmosphere have been conducted over the past four decades, and these have contributed much to our understanding of the properties of the incoming primary radiation and its interaction with the atmosphere. In addition, the atmosphere has provided us with a unique high energy physics laboratory, where experiments can be conducted at particle energies beyond the capabilities of any ground-based laboratories. An opportunity is thus provided to design experiments to test the predictions of theories of high-energy radiation transport in low-z media.

The HASL balloon program of cosmic-ray measurements, commenced in 1968, was designed to provide accurate data on charged particle ionization and flux throughout the atmosphere. Two applications were envisaged: (1) to provide basic information relevant to the potential exposure of aircraft crews and passengers to ionizing radiation, and (2) to provide critical tests for analytical calculations of the properties of cosmic radiation throughout the atmosphere, particularly those being conducted here by O'Brien (refs. 1 and 2). In this paper, we summarize our results to date, critically compare them with earlier data, and discuss their relevance to theory.

II. EXPERIMENTAL PROGRAM

Our initial cosmic-ray measurements at ground level (0 to 12,000 feet) in the continental United States were made to estimate this source of radiation exposure of the whole population. A high pressure argon ionization chamber was utilized, and its gamma-ray response was corrected for by means of concurrent measurements with a gamma scintillation spectrometer. The results obtained in 1965, primarily in Colorado, were reported by Lowder and Beck (ref. 3), and a recheck of these data in 1968 yielded essentially the same results.

These ionization profiles were extended to altitudes above 12,000 ft. by a series of balloon flights conducted beginning in 1968 with the cooperation of the United States Air Force balloon team at Goodfellow Air Force Base in San Angelo, Texas, the NCAR Scientific Balloon Base in Palestine, Texas, and the University of New Hampshire. The flights to be discussed are listed in Table I, along with the instrumentation included in each flight package. The basic instrument in each flight was a pressurized argon ionization chamber for total charged particle ionization determination. On two flights, a specially designed dual Geiger tube package was included, to provide particle flux data. Other types of ionization chamber are being flown, and the University of New Hampshire scintillation spectrometer has provided much information on charged particle and photon fluxes. However, the analysis of these results is not yet complete, and we restrict our attention here to the argon chamber and Geiger counter data.

TABLE I

HASL BALLOON FLIGHTS, 1969-70

			Ionization Chambers			
Date	Site	Geom. Lat.	Gas (atm.)	Wall (g/cm^2)	Volume (ℓ)	Other Instrumentation
5/27/69	Durham, N. H.	54°N	9.0 Ar	1.1 Fe	2.8	UNH scintillation spectrometer
11/16/69	Palestine, Tex.	42°N	(1) 9.2 Ar (2) 27.5 Ar	0.5 Fe 2.7 Fe	2.8 2.8	UNH scintillation spectrometer
4/9/70	Sioux City, Ia.	52°N	(1) 22.9 Ar (2) 0.9 TE	1.1 Fe 0.5 Fe	2.8 8.2	- -
4/16/70	Sioux City, Ia.	52°N	22.9 Ar	1.1 Fe	2.8	dual GM counters
6/7/70	Palestine, Tex.	42°N	22.9 Ar	1.1 Fe	2.8	UNH scintillation spectrometer + dual GM counters

III. IONIZATION MEASUREMENTS

The ionization measurements were carried out with pressurized argon ionization chambers similar to those used in the long series of measurements conducted by the group led by H. V. Neher at the California Institute of Technology. Basically, they are hemispheres of type 304 stainless steel welded together to form 7 or 10 inch diameter spherical shells. The collecting electrode is a 0.75 inch diameter steel sphere mounted on a rigid steel tube attached to a triaxial metal-to-ceramic seal welded to the outer shell. The gas filling is ultra-high-purity argon. Chambers with various wall thicknesses and filling pressures were fabricated, to permit study of the effect of these parameters on the inferred free air ionization. Our "standard" chamber has been one filled to 23 atmospheres surrounded by 55 mil (1.1 g/cm^2) steel walls.

The output current from the chamber is measured with a HASL designed solid-state electrometer using a MOSFET (metal-oxide-semiconductor field-effect transistor) as the input element. This electrometer is an improvement over one described by Negro, Cassidy, and Graveson (ref. 4), with the high input impedance and low leakage current capability required by this type of measurement. The voltage output of this electrometer is recorded on-board by a Rustrak strip-chart recorder.

Figure 1 shows one of the ionization chamber systems mounted in its flight package.

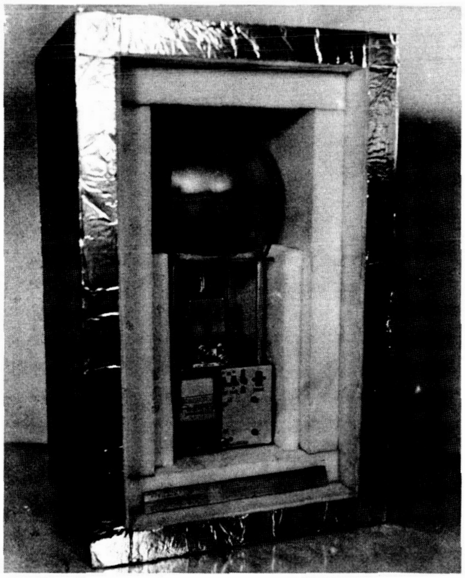

Figure 1. HASL pressurized argon ionization chamber mounted in balloon flight case.

The absolute calibration of the response of these chambers is complicated by the absence of any known "standard" cosmic radiation fields to check our laboratory or armchair calibration procedures. These procedures can be divided into four steps:

(1) calibration of the output of the data recorder in terms of the output voltage of the MOSFET electrometer,
(2) calibration of the output voltage of the electrometer in terms of input current from the ionization chamber,
(3) calibration of the output current of the chamber in terms of ion pairs produced per cm^3 of filling gas reduced to STP,
(4) conversion of absolute ionization (STP) within the chamber to absolute ionization in free air.

Each of these steps is discussed in detail by Raft, Lowder, and Beck (ref. 5), taking into account the experience gained from previous experimental programs of a similar nature. We concluded there that the treatment of these ionization chambers as essentially argon cavities in an air medium is basically correct. Any significant deviation from this circumstance would manifest itself as discrepancies among the free air ionization values inferred from the responses of chambers with differing wall thicknesses or gas fillings. Our calibration is essentially identical to that used by the Caltech group, and should yield comparable ionization values.

The ionization data from the flights listed in Table I are summarized in Table II. The two Sioux City flights are combined, as the three argon chambers yielded essentially identical results. Also indicated are the data from the Colorado ground measurements in 1965 and 1968. The conversion factor indicated at the bottom of the table permits the conversion of the charged particle ionization data to free air dose rate units. Particular note should be taken of the fact that these data all pertain to a period near solar activity maximum in the 11 year cycle, when the cosmic radiation intensity is near minimum.

TABLE II

IONIZATION AND AIR DOSE RATE PROFILES, 1969-70

Atm. Depth (g/cm^2)	Altitude (feet)	Ionization (I) Durham (5/69)	Sioux City (4/70)	Palestine (11/69)	Palestine (6/70)	Colorado ('65, '68)
20	87,200	285	-	195	165	-
50	67,900	290	282	232	201	-
75	59,500	280	266	230	206	-
100	53,500	254	248	214	197	-
150	45,100	198	198	183	166	-
200	39,100	155	156	136	128	-
250	34,400	110	112	109	97	-
300	30,500	78	80	76	73	-
350	27,100	54	55	55	52	-
400	24,000	38	38	38	37	-
450	21,300	28	28	28	27	-
500	18,800	20	21	19	20	-
550	16,400	15	15	14	15	-
600	14,300	11	11	9.8	10.5	12:
700	10,400	6.5:	7.1	5.9	6.5	7.2
800	6,900	4.3:	4.9	4.3	4.2	4.3
900	3,800	3.3:	3.3:	-	2.8	2.9
1033	0	-	-	-	-	2.1

*"I" → ion pairs/cm^3/sec/atm. air at STP; 1I ≡ 1.50 µrad/hr.

Although it is always hazardous to compare different sets of cosmic-ray measurements displaced in space and time, the latitude effect is clearly discernable at altitudes above 35,000 ft., as is the significant profile change at a single location (Palestine) for two flights separated by seven months. It is impossible to ascertain whether this latter phenomenon represents a long-term trend, or is the result of particular conditions pertaining on the dates of the flights.

The low-altitude data is in reasonable agreement with our ground measurements, particularly those from the June 1970 Palestine flight which we believe to be the most reliable at great depths. The higher values for the Colorado data at 600 and 700 g/cm^2 may be due to the latitude effect and to the fact that the 1965 data were obtained near cosmic radiation intensity maximum of the 11 year cycle.

No significant differences between the ionization values inferred from chambers with different wall thicknesses and filling gas pressures have yet been noted. This tends to indicate that the distortion of the free air radiation field produced by the chamber has little effect on the observed ionization. Future flights should enable us to quantitate whatever small effects that may exist.

IV. PARTICLE FLUX MEASUREMENTS

The Geiger tube package consists of one tube mounted vertically and the other horizontally with the ratemeter outputs recorded by on-board Rustraks synchronized with those indicating the ionization chamber responses. The Geiger tubes are 7.0 cm long and 19 cm diameter, with 30 mg/cm^2 Al walls. The calibration of these counters has been described by Keppler (ref. 6) and we have adopted his results. The detection efficiency for charged particles is 0.96, and for photons is < 0.01 from 0.05 to 1 MeV, increasing to 0.1 at 6 MeV. The geometry factors are such that the geometric mean of the count rates of the two counters is ten times the omnidirectional particle flux for $\cos^n\theta$ distributions of the incoming particles with n ranging from 0 to 3. The detector calibration is thus essentially independent of atmospheric depth, since the angular distribution of the incident particles closely satisfy these conditions throughout the atmosphere.

The inferred particle fluxes obtained on two flights in 1970 are given in Table III. The Sioux City flight data (52° N) were obtained nearly two months earlier than the Palestine data (42° N), but the two profiles agree closely at depths greater than 200 g/cm². The divergence at lesser depths reflects the latitude effect.

The observed counting rates of the Geiger tubes include some photon-initiated counts that would produce an overestimate of the charged particle flux. It is well known that the photon flux in the atmosphere is of the order of ten times the electron flux (e.g., see ref. 7), and that the electrons make up the bulk of the charged particle flux throughout most of the atmosphere. Anderson's data (ref. 7) indicates that most of the photons are between 10 and 1000 keV in energy, implying a detector efficiency of less than 1 percent for this component. Thus, the photon contribution to the flux measurement is < 10 percent.

We can relate the measured particle flux data to the ionization results for the same flights to estimate the mean specific ionization per particle as a function of atmospheric depth. These figures are also shown in Table III, and indicate a nearly constant value for this parameter of ~100 ion pairs/cm (STP air) between 20 and 500 g/cm² (correcting for photons). This result is somewhat unexpected, particularly at the highest altitudes where a significant contribution from high specific ionization particles might be anticipated. There is no evidence for this on either flight.

The sea level figures given in Table III are derived from the flux value given by Rossi (ref. 8) and the sea level ionization value estimated by Lowder and Beck (ref. 3).

TABLE III

CHARGED PARTICLE FLUX AND SPECIFIC IONIZATION, 1970

Atm. Depth (g/cm²)	Particle Flux (cm^{-2} sec^{-1})* 52° N	42° N	Mean Specific Ionization (ion pairs/cm)
20	2.63	1.72	95
50	2.72	2.19	95
70	2.68	2.25	94
100	2.49	2.17	93
150	2.05	1.81	92
200	1.48	1.40	91
250	1.04		96
300	0.76		96
350	0.52		98
400	0.37		102
450	0.28		96
500	0.20		100
550	0.16		93
600	0.13		82
1033	(0.025)		(85)

*Uncorrected for photon counts, which amount to < 10 percent of the total (see text).

V. COMPARISON WITH OTHER EXPERIMENTS

The standard data on cosmic-ray ionization in the atmosphere have long been the results obtained by the Caltech group over several decades (see e.g., Neher, ref. 9). Our ground level results (ref. 3) were observed to disagree with comparable measurements by this group, and this disagreement now extends to all altitudes. George's data (ref. 10), obtained in January 1968 on airplane flights over the southwestern United States, can be directly compared to our Texas results in 1969 and 1970, and this comparison indicates a 20 percent discrepancy extending from 200 g/cm² depth to sea level (ref. 5). A discrepancy of about the same magnitude has been noted by Winckler (ref. 11) between his results and comparable Caltech data. There may exist some subtle error in the ionization chamber calibration procedures used by the various groups, and experiments are now planned to resolve this uncertainty. Barring any unexpected systematic errors of this type in our calibrations, which the redundancy built into our procedure as well as agreement with other data render highly unlikely, we believe the ionization results reported here to be accurate to ~5 percent.

The particle flux data are comparable to those obtained by Anderson (ref. 7) and others. However, the overall accuracy is somewhat poorer than that estimated for the ionization results, partly due to the uncertainty in the correction for photon counts as well as the poorly known angular distributions of the incident particles.

Further balloon experiments are being planned to provide more data at various latitudes and near solar activity minimum. The results from the various types of ionization chambers, as well as the anticipated laboratory intercomparisons, should resolve most existing uncertainties in the data and provide additional information on the properties of the atmospheric radiation field.

VI. COMPARISON WITH THEORY

At this symposium, O'Brien (ref. 1) has compared his calculated ionization values near cosmic-ray intensity maximum with the appropriate Caltech data. More recent calculations permit a comparison with our data near cosmic-ray intensity minimum. The ionization profiles at 42° N latitude are shown in Figure 2 and the charged particle flux profiles at the same latitude are given in Figure 3. Measured and calculated dose rates at four important altitudes are given in Table IV, along with the calculated tissue dose rate from all components. The agreement between theory and experiment is in general surprisingly good. The observed differences can be readily understood on the basis of the transport approximations introduced into the calculations, particularly the non-transport of the electromagnetic cascade energy from the point of neutral pion decay and the assumption of zero upward directed flux near the top of the atmosphere. Both effects would tend to pile up the absorbed energy near the Pfotzer maximum. At great depths, where these effects are minimal, the discrepancy becomes small. We regard the experimental data as providing strong evidence for the validity of the theory, within the limitations of the necessary approximations introduced.

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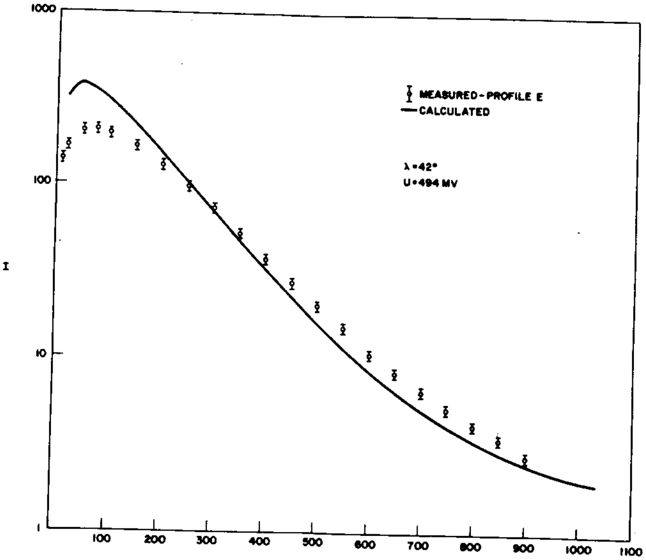

Figure 2. Experimental and theoretical ionizati n profiles in the atmosphere, Texas, 1970.

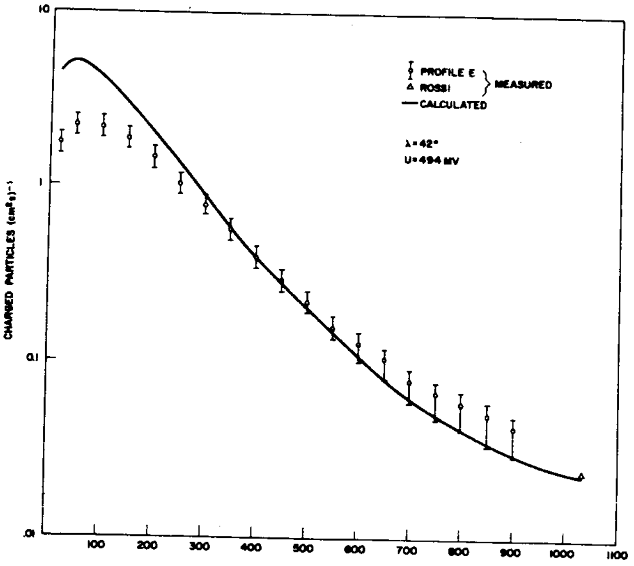

Figure 3. Experimental and theoretical charged particle flux profiles in the atmosphere, Texas, 1970.

TABLE IV

COMPARISON OF MEASURED AND CALCULATED DOSE RATES NEAR SOLAR MAXIMUM

	Charged Particle Air Dose Rates		
Altitude	Measured (μrad/hr)	Calculated (μrad/hr)	Total Tissue Dose Rates Calculated*
Sea Level	3.1	3.0	3.0
10,000 ft.	9.5	8.7	11
35,000 ft.	170	180	210
65,000 ft.	436	611	800

*Dose rates calculated for 5 cm depth in tissue slab.