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MEASUREMENTS OF COSMIC-RAY CHARGED PARTICLE IONIZATION AND FLUX DENSITIES IN THE ATMOSPHERE

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ABSTRACT

The results of ionization rate and flux density measurements of cosmic-ray charged particles with balloon-borne, high-pressure argon ionization chambers and GM counters are presented for flights from Cape Girardeau, Missouri, in September 1972 and from Fort Churchill, Manitoba, in July 1973. Ionization rate data from Health and Safety Laboratory equipment are compared with measurements made on the same flights with a standard California Institute of Technology argon chamber which has been used for many decades to obtain profiles of cosmic-ray ionization rates in the atmosphere. It is tentatively concluded from these comparisons and other evidence that the latter measurements overestimate the ionization rates by about 10 percent.

INTRODUCTION

Cosmic-ray charged particles contribute significantly to man's dose from environmental radiation. A recent NCRP report[1] estimates that the average dose-equivalent in a year to the gonads, bone marrow, and G.I. tract is 28 mrem/y from this source for the U. S. population. This is approximately 35 percent of the total from all external and internal natural sources.

The intensity of charged particles in the atmosphere is usually expressed in terms of flux density or of air ionization rate (ion pairs per cm^3-s-atm at STP). These quantities can be related to the absorbed dose rate in free air and, by means of certain assumptions that account for body and structural shielding, to tissue and organ dose and dose-equivalent rates.

Most of the early measurements of cosmic-ray ionization rate in the atmosphere at various latitudes, altitudes, and phases of the 11-year solar activity cycle were made by the group at the California Institute of Technology (CIT) under the direction of R. A. Millikan and H. V. Neher. Since 1971, their work has been continued by H. R. Anderson at Rice University. Our measurements have indicated that there may exist some systematic differences in the published ionization values[2,3]. This problem has been subsequently discussed by several investigators[4-8]. Intercomparisons of existing data tend to indicate that the CIT-Rice results are 15-20 percent higher than the more limited data obtained by the other workers. However, such intercomparisons of data obtained at different times and places are rendered somewhat imprecise by the complex variations of cosmic-ray intensity particularly at high altitudes.

In this report, we present the results of two balloon-borne experiments, where intercomparisons between the ionization rate data obtained simultaneously from the CIT ionization chamber used by Anderson and from HASL chambers are possible. The observed 6 percent discrepancy is somewhat less than that noted previously. During the several years since these results were obtained, no obvious explanation for this discrepancy or its apparent change with time has been developed. However, some recent data, notably a comparison of the cosmic-ray responses of our ionization chambers and LiF thermoluminescence dosimeters[9] and some cosmic-ray ionization rate measurements on large bodies of water by Kyker and Liboff[8] with a large air-filled ionization chamber, provide evidence for the validity of the calibrations of the HASL chambers.

Our tentative conclusion is that the data from the CIT chamber overestimate the cosmic-ray ionization rate in free air by about 10 percent.

IONIZATION RATE MEASUREMENTS

A cooperative HASL-Rice program of laboratory experiments and high-altitude balloon flights was undertaken in 1972 and 1973. Four balloon experiments were made with various instrumentation (see Table 1). The results from the first two flights have been analyzed and compared in detail. The more limited data from the last two flights were less satisfactory for comparison purposes, but the HASL results were consistent with the data from the initial Fort Churchill flight. Of particular importance are the comparisons of the data obtained with the standard CIT-Rice chamber (25 cm diameter, 0.4 g/cm^2 steel walls, 8 atm argon filling) and a similar HASL chamber (25 cm diameter, 0.5 g/cm^2 steel walls, 10 atm argon filling).

Figure 1 shows the ionization rate vs. pressure-altitude profiles obtained with the Rice and HASL standard chambers during the July 9, 1973 flight from Fort Churchill. The ratio between them is also plotted, at intervals of 20 g/cm^2 between 20 and 300 g/cm^2 depth. It is evident that the Rice/HASL ratio is approximately constant with altitude, averaging 1.06. Two important points should be noted: 1) this flight is the only one of the four where the data were recorded in a synchronous manner, so that there was no ambiguity in the time scale or in the pressure-altitude measurements; 2) the ratio is significantly less than those indirectly inferred from previous flights prior to the direct intercomparison program. The detailed data from the HASL instruments are given in Table 2.

The data shown in Table 3 from the September 11, 1972 flight from Cape Girardeau, Missouri, were analyzed in the same way and, as Table 4 shows, the ratio indicates an altitude dependence that is inconsistent with the Fort Churchill results. However, an arbitrary correction of one minute in the relative times as indicated in the table yielded an approximately constant ratio of 1:06 that agrees with that obtained in the later flight. We regard this as supportive evidence for the ratio obtained in the Fort Churchill flight.

These high-altitude intercomparisons indicate that the CIT-Rice chambers were calibrated in such a manner as to yield absolute air ionization rate data that are 6 percent higher than those inferred from the HASL chamber calibration. This deviation is not sensitive to the significant changes in the composition of the particle flux that exist in this altitude range.

This conclusion is supported by the results of a laboratory intercalibration of the CIT-Rice and HASL standard chambers with a ^{60}Co source of known strength. The former chamber read 20 percent too high when its cosmic-ray calibration factor was applied to the output reading, rather than the 10 percent expected from our estimates of the gamma-ray wall effect in such chambers[10].

The results indicate that the difference in ionization rates inferred from the two chambers may be attributable to problems in the determination of the ionization rate in the argon filling gas rather than in the conversion of this ionization rate to ionization rate in free air. Moreover, it appears that the HASL data in the two types of radiation field are more nearly consistent with theoretical expectations.

George[4] compared the ionization rates inferred from a CIT-Rice standard chamber with those inferred from a large, thin-walled (plastic), air-filled chamber at various atmospheric depths. At depth less than 500 g/cm^2, the argon-filled chamber indicated about a five percent higher ionization rate than the air-filled chamber. At greater depths, the agreement was much closer and both chambers read 2.6 I at sea-level over water. Other measurements of the cosmic-ray ionization rate in the lower atmosphere[2,7,8], as well as values obtained from atmospheric radiation transport calculations[11] and experimental measurements of charged particle flux densities[1], tend to indicate that the sea-level ionization rate is about 2.1 - 2.2 I. Although the statistics are relatively poor for measurements on balloons at large atmospheric depths, all profiles of ionization rate determined with HASL ion chambers are consistent with the profile determined from our previous ground-based measurements[2], which were based on an ionization rate value of 2.1 I at sea-level.

Recently, the absorbed dose rates in free air inferred from ^7LiF thermoluminescence dosimeters as used for environmental radiation monitoring and our 25 atm argon, 2.6 g/cm^2 steel-wall, 8 liter ionization chambers were compared[9]. The measurements from three field sites and within the HASL whole body counter shield agreed to within a few percent. The close agreement of these dose rates, particularly those inferred in the nearly pure muon field within the whole body counter shield, tends to confirm the cosmic-ray calibrations of both detectors, which were derived partly from theoretical considerations[9,10].

We have tentatively concluded that a correction of approximately 10 percent on the published ionization rate data obtained by the CIT and Rice groups is required. These corrected results and HASL data have been used to derive altitude profiles of cosmic-ray charged particle ionization rates and absorbed dose rates in free air at several geomagnetic latitudes and at solar activity maximum and minimum[1].

OTHER FINDINGS

The ionization rate data in Tables 2 and 3 were mainly derived from the HASL 10 atm argon-filled ion chamber. Two other HASL chambers were flown on the July 9, 1973 flight, a similar chamber filled with 10 atm of air and a 25 atm argon chamber with 2.6 g/cm^2 steel walls (8 liters volume). The ratio of the responses of the two argon-filled chambers provided a measure of the effect of the steel wall thickness on the measured ionization within the chambers. The magnitude of this effect at atmospheric depths where the electron-photon component is dominant is consistent with the calculations of Beck[12]. The ratio of the responses of the two thin-walled chambers, filled with 10 atm of air and argon, respectively, is consistent with estimates of the effect of ion recombination in the air-filled chamber.

Also included in Table 2 are estimates of the charged particle flux density, derived from the counting rates of two Geiger tubes. These tubes are 7.0 cm long and 1.9 cm diameter, with 30 mg/cm^2 Al walls. The calibration of these counters has been discussed by Keppler[13]. One of these tubes is mounted vertically and the other horizontally, and the geometry factors are such that the geometric mean of the count rates is ten times the omnidirectional charged particle flux density[6]. No correction has been made for photon-initiated counts, which contribute less than 10 percent of the total counting rate[6].

The flux density data agree well with earlier results obtained on two flights in 1970[6], taking into account the differences in solar activity and geomagnetic latitude. The mean specific ionization of the incident particles in the last column of Table 2, calculated from the ratio of ionization rate to particle flux density, show a slow rise with decreasing atmospheric depth to about 50 g/cm^2, and then a more rapid increase at lesser depths. This latter increase undoubtedly reflects the contributions of primary protons and alpha particles of relatively high LET.

The 1973 Fort Churchill flights were the last in our balloon flight program. The data have provided some insight into the nature and extent of the uncertainties in measurements of cosmic-ray ionization rates in the atmosphere. Our results have been integrated with the more extensive data from the CIT-Rice program to derive typical profiles of cosmic-ray ionization rates in the atmosphere(1), which can be used for estimating dose to man.

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TABLE 1

INTERCOMPARISON BALLOON-BORNE MEASUREMENTS

Date	Location	Geom. Lat.	Instrumentation
Sept. 11, 1972	Cape Girardeau, Mo.	46°	A,B
July 9, 1973	Fort Churchill, Manitoba	69°	A,B,C,D,E
July 14, 1973	" "	69°	A,B
July 20, 1973	" "	69°	A,B

Key to Instrumentation:

A. CIT-Rice 8 atm argon ion chamber, 0.4 g/cm^2 Fe wall.
B. HASL 10 atm argon ion chamber, 0.5 g/cm^2 Fe wall.
C. HASL 10 atm air ion chamber, 0.4 g/cm^2 Fe wall.
D. HASL dual GM counter package.
E. HASL LiF TL dosimeter package.

TABLE 2

DATA FROM FORT CHURCHILL FLIGHT, JULY 9, 1973

Atmos. Pressure (g/cm^2)	Ionization Rate (ion pairs/cm^3-s-atm)	Charged Particle Flux Density (per cm^2-s)	Specific Ionization (ion pairs/cm)
737	6.1		
675		0.106	83
643	10.0	0.125	80
615	11.5	0.154	75
588	13.7	0.163	84
560	14.8	0.182	81
535	19.5	0.216	89
510	21.2	0.238	89
485	25.2	0.314	80
463	31.2	0.344	91
437	37.3	0.417	89
415	45.9	0.440	104
392	51.8	0.531	98
368	59.1	0.626	94
350	67.5	0.732	92
379	79.5	0.849	94
310	86.8	0.97	89
292	107	1.09	98
276	116	1.23	94
262	131	1.36	96
248	143	1.42	101
237	149	1.51	99
227	157	1.70	92
216	170	1.77	96
206	180	1.82	99
195	187	1.94	96
185	205	2.10	98
175	221	2.22	100
164	233	2.39	97
154	249	2.51	99
143	262	2.57	102
134	269	2.75	98
124	294	2.87	99
114	303	2.98	102
105	318	3.13	102
97	323	3.20	101

TABLE 2 (Cont'd)

Atmos. Pressure (g/cm^2)	Ionization Rate (ion pairs/cm^3-s-atm)	Charged Particle Flux Density (per cm^2-s)	Specific Ionization (ion pairs/cm)
92.5	330	3.31	100
87.5	348	3.31	105
83.0	357	3.49	102
78.0	371	3.55	105
72.5	367	3.53	104
67.5	373	3.60	104
62.5	391	3.69	106
57.0	395	3.85	103
54.2	405	3.89	104
52.0	402	3.90	103
50.0	418	3.95	106
47.5	425	3.97	107
44.5	424	3.89	109
42.0	433	3.91	111
39.0	422	3.96	107
36.5	425	3.94	108
34.0	435	3.92	111
31.5	444	3.88	114
29.2	425	3.94	108
27.0	457	3.91	117
25.3	464	4.01	116
23.6	459	3.91	117
22.1	460	3.95	116
20.8	460	3.94	117
19.7	459	3.90	118
17.7	455	3.88	117
15.2	465	3.90	119
12.7	464	3.79	122
10.3	475	3.83	124
9.5	471	3.73	126
8.7	470	3.76	125
7.8	471	3.69	128
6.9	492	3.66	134
6.5	488	3.75	130
6.4	491	3.65	135
6.3	487	3.64	134
6.2	485	3.66	133

TABLE 3

DATA FROM CAPE GIRARDEAU FLIGHT, SEPTEMBER 11, 1972

Atmospheric Pressure (g/cm^2)	Ionization Rate, I (ion pairs/cm^3-s-atm)
782	4.9
739	6.3
711	7.3
662	9.6
619	12.2
583	14.8
538	19.0
479	26.9
451	34.0
409	41.6
390	51.2
359	62.3
336	75.0
315	89.7
286	105
263	121
242	140
220	160
195	181
182	196
165	216
150	229
139*	243
4*	230

*Data lost between 139 and 4 g/cm^2. A nearly identical profile at Mitchell, SD in October 1969 indicates a maximum ionization rate of 320 I at 50 g/cm^2.

TABLE 4

IONIZATION PROFILE COMPARISONS

	I_{Rice}/I_{HASL}		
P (g/cm²)	CG_1	CG_2	FC
20	-	-	1.061
40	-	-	1.067
60	-	-	1.070
80	-	-	1.065
100	-	-	1.082
120	-	-	1.073
140	1.033	1.062	1.051
160	1.027	1.073	1.041
180	1.025	1.066	1.037
200	1.011	1.056	1.053
220	1.013	1.063	1.066
240	-	-	1.068
260	-	-	1.053

Key:

I → Measured ionization rate (ion pairs cm^{-3} s^{-1} atm^{-1} at STP).

CG_1 → Cape Girardeau flight, direct comparison of independently determined I vs. P profile.

CG_2 → as CG_1, except 1 minute subtracted from Rice time scale for pressure determination.

FC → July 9, 1973 Fort Churchill flight.

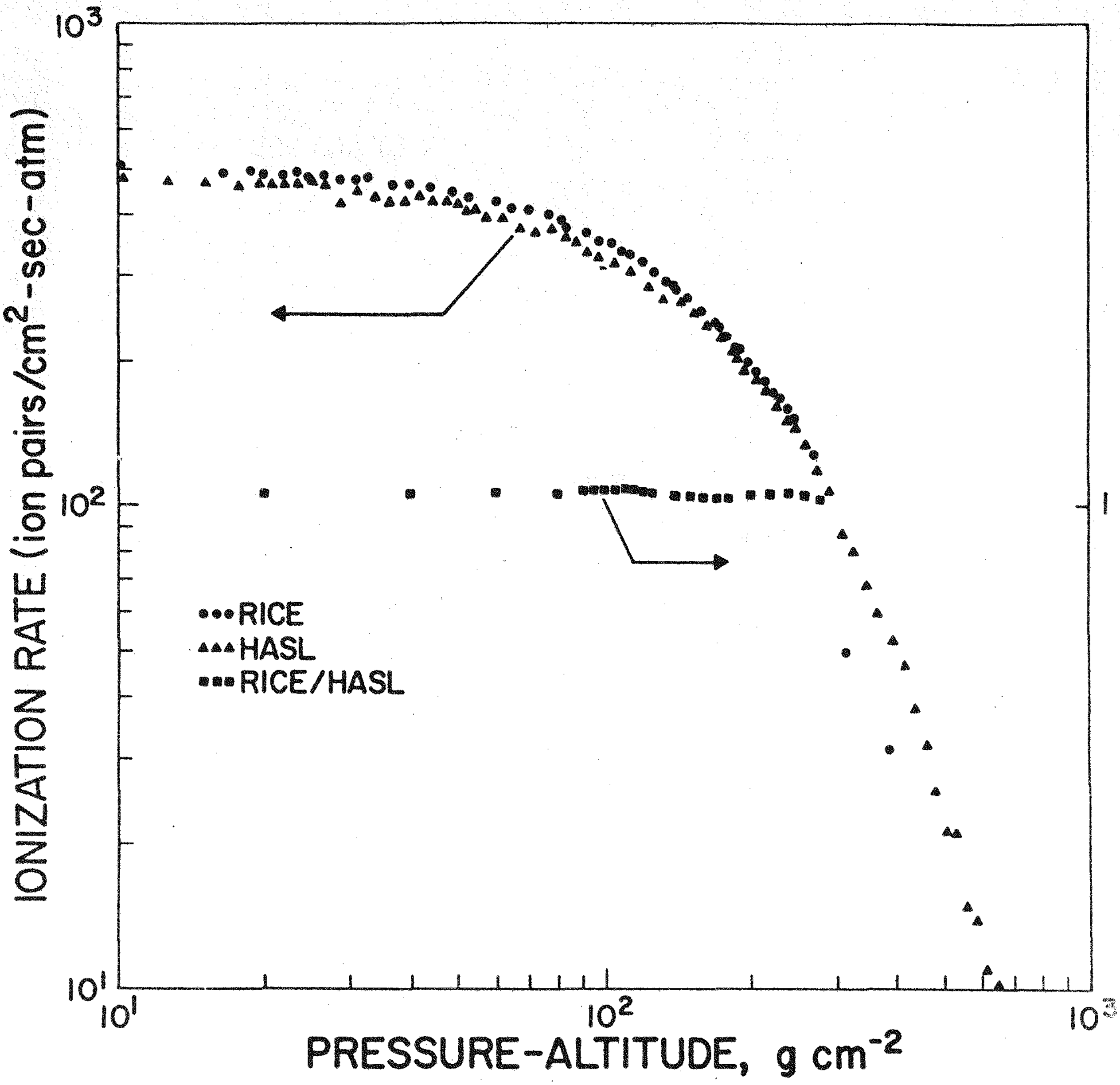

Figure 1. Cosmic-ray ionization measurements - Fort Churchill, July 9, 1973.