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Barometric and Temperature Coefficients of Frequency of Small Cosmic-Ray Bursts and of Burst-Corrected Cosmic-Ray Ionization*

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Barometric and (surface) temperature coefficients are determined for a class of cosmic-ray bursts consisting of 1.2 to 1.9×10^6 ion pairs in argon at 20 atmospheres in a heavily shielded chamber, as well as for the burst-corrected ionization.

For the bursts the coefficients (particularly the temperature coefficient) are found to depend upon whether the multiple regression coefficient and partial correlation coefficient are computed from daily averages for individual months or for all 581 days, the latter yielding a positive temperature coefficient of 0.24 percent/°C, in which confidence is somewhat lacking because it depended upon four readers. For the bursts, the averages of the coefficients for 19 individual months are −1.54 percent/mm Hg and −0.98 percent/°C, while the averages for those months with significance ratios above the 2 percent level are −2.44 percent/mm Hg and −1.66 percent/°C.

For the burst-corrected CR ionization, the averages of the coefficients for 19 individual months are −0.154 percent/mm Hg and −0.038 percent/°C, while the values computed for 581 days are −0.174 percent/mm Hg and −0.056 percent/°C. Little differences from the latter values are found with computations based on monthly means.

Comparisons are made with earlier observations with the same chamber containing air at 160 atmos and with the observations of other experimenters and the relations of these to the explanation of the temperature dependence in terms of meson decay developed by Blackett and Duperier are discussed. Values for the mean free paths of the radiations producing the small bursts and the burst-corrected ionization are deduced on the basis of their respective barometric coefficients.

I. INTRODUCTION

IN a recent paper[1] the writer reported an investigation of the relation of the frequency of occurrence of a class of small cosmic-ray bursts to areas of sunspots and certain other variables. The data employed were obtained at Boulder, altitude 1646 m, geomagnetic latitude 49° N, by V. A. Long and R. M. Whaley during a period of 18 months in 1938–1939. There was found to be a lack of close correlation between the frequency of the small bursts and the cosmic-ray (CR) ionization after correction for bursts, and certain differences among the relations of these two variables to others. In the discussion it was pointed out that (as observed by others[2,3]) the small-burst frequency displayed much larger barometric coefficients for most of the months for which they were computed than was displayed by the burst-corrected CR ionization. These facts appeared to provide evidence that the small bursts were produced by a different type of radiation from that responsible for the major portion of the ionization after correction for bursts, although the heavy shielding permitted only quite penetrating radiations to enter the ionization chamber.

An opportunity arose to obtain a second series of continuous CR ionization records during a little more than 19 months from October 21, 1947, to June 1, 1949, inclusive. In addition to computing the barometric coefficients for the remaining months of the first series, barometric and also outdoor (surface) temperature coefficients have been computed for the new series.

II. APPARATUS

Considerable information regarding the high pressure-ionization-chamber, recording equipment has been given elsewhere.[4–8] For the 1938–1939 series, air at 160 atmos was employed, while for the 1947–1949 series, argon at 20.2 atmos was used. Further details are given in Appendix I.

The outdoor temperature and relative humidity were obtained from good recording instruments mounted about 5 ft above the ground in a well-ventilated shelter. Barometric pressure was recorded on a good microbarograph. Magnetic data were supplied from the Tucson (Arizona) Magnetic Observatory of the U. S. Coast and Geodetic Survey.

III. EXPERIMENTAL PROCEDURE

Apart from the employment of more convenient switching arrangements and more accurate meters for calibration, etc., the experimental procedure during the recent series of measurements which is described here did not differ much from that of the earlier series. The central system was grounded to its guard for one minute of each hour by means of an electric clock. By application of definite potentials to the central system for short intervals, the sensitivity of the electrometer was recorded on the photographic record each day just at the beginning and end of the daily record. In order to facilitate the reading and classification of bursts, the sensitivity was maintained very nearly constant with the exception of a period of three months, July 28 to October 27, inclusive, 1948, during which the records were not read promptly and a decrease of 10 percent in

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[1] J. W. Broxon, Phys. Rev. **72**, 1187 (1947).

[2] Steinke, Gastell, and Nie, Naturwissenschaften **21**, 898 (1933).

[3] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **47**, 429 (1935).

[4] J. W. Broxon, Phys. Rev. **37**, 1320 (1931).

[5] J. W. Broxon, Phys. Rev. **42**, 321 (1932).

[6] R. M. Whaley, thesis, University of Colorado (1940).

[7] J. W. Broxon, Phys. Rev. **38**, 1704 (1931).

[8] V. A. Long, thesis, University of Colorado (1940).

the sensitivity went unnoticed. This variation was corrected by Dr. Long (most experienced of the readers; reader A of the first series and 1 of the second) in the detailed reading of the records for this period. The vane potential and the applied ion-collecting potential were also read daily and maintained very nearly constant; the ion-collecting potential was given by a good microammeter in series with the high resistances of the capacitance-resistance bridge arrangement and was maintained extremely nearly constant. P_2O_5 was usually renewed twice a week in both the insulating box and the guard system, although occasionally the latter was renewed only once a week. The argon pressure was observed daily. Since the chamber had contained air at 2400 lb/in.^{2} for some years, no leak was anticipated or observed.

Calibrations of the CR apparatus were carried out carefully during the 1938–1939 measurements,[6,8] electrostatic induction coefficients being determined by employment of a Harms air condenser calibrated by the National Bureau of Standards. These were employed for the recent series after correction for the small changes resulting from the modifications described in Appendix I.

IV. READING OF RECORDS

In reading records from the microbarograph, thermograph, etc., an estimate was made visually of the average value for each hour as indicated by the graph. These values were recorded, and the average of the 24 hourly values for a G.M.T. day was taken as the average for that day.

The CR ionization records were read through a reading glass by means of a transparent millimeter scale maintained perpendicular to the time axis. In addition to the displacements at the initiation and termination of each 59-min collecting period, all bursts producing a sudden deflection of 1 mm or more were read, all readings being estimated to 0.1 mm.

Before beginning to read the CR records for the 1938–1939 series, Long[4] gave particular attention to the problem of distinguishing between bursts and statistical fluctuations, considering particularly the work of Evans and Neher,[9] and Bennett, Brown, and Rahmel.[10] He computed the maximum time for collection of all the ions of a burst in the air at 160 atmos as used for the earlier observations to be 28 sec, and by running the drum holding the photographic paper at 12 times its normal speed he found the maximum time experimentally to be 25 sec. Considering the normal rate of advance of the photographic record, he found that a burst producing a deflection of 1 mm (the smallest read) should cause the photographic record to deviate not more than 8° from the normal to the time axis, while deflections for larger bursts should deviate correspondingly less. All bursts of that series were selected on this basis.

Following Bennett, Brown, and Rahmel,[10] Long computed the probability that one of the apparent 1-mm bursts of the earlier series might actually have been the result of statistical fluctuation of the radiation responsible for the burst-corrected ionization. He found the probability to be only 0.1 percent for 1-mm bursts and less for larger ones, of course.

For the 1947–1949 series, the maximum time for the collection of all of the ions of a burst in the radial field employed was computed, assuming a mobility of 1.37 cm/sec per v/cm for the slowest ions in argon at atmospheric pressure, to be 3.4 sec. With the photographic paper advancing at the rate of 20 in. in 25 hr along the time axis, a 1-mm burst should correspond to a deflection in the record deviating just 1° from the normal to the time axis, while larger bursts should deviate less. Actually, all bursts down to 1 mm seemed to be practically perpendicular to the time axis, and appeared as quite clear breaks in the photographic record. The much shorter interval for collection of the ions in the later series would appear to make it less likely than in the earlier series that a supposed burst of 1 mm should actually represent a statistical fluctuation, in spite of the increase in the sensitivity of the electrometer.

Doubtless the most convincing criterion for the reality of the bursts is the fact that they are always in the sense indicating a sudden increase rather than a decrease in the ionization in the high-pressure chamber. This condition was almost wholly fulfilled. On about a dozen occasions there appeared to be "negative" bursts. It was thought at first that these might represent rare events in the compensating condenser. It was later found, however, that such deflections could be produced by a conductor which inadvertently had been left so that it could occasionally make contact with one terminal of the high potential system and thereby affect the potential of the central system. It was concluded that only one or possibly two of the supposed "negative" bursts could not be explained entirely satisfactorily on this basis. The many thousands of bursts recorded (there were an average of about 10 per hour in the 1- to 1.5-mm class during the 582 days for which records were obtained) were otherwise all in the positive sense.

Usually 10 to 20 min of one hour of each day were required for calibration, checking potentials, inserting dryer, changing the record, etc. For such hours the number of 1-mm bursts and the burst-corrected ionization current were corrected for the time lost on the assumption that they would have continued at the same rate for the normal collection period of 59 min., the latter not being adjusted to the 60 min/hr. On other occasions records for one or more hours of a day were lost because of adjustment of apparatus, poor photographic conditions, etc. These were similarly corrected to correspond to a full 24-hr day. In no event

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[9] R. D. Evans and H. V. Neher, Phys. Rev. 45, 144 (1934).

[10] Bennett, Brown, and Rahmel, Phys. Rev. 47, 437 (1935).

was the record for an hour retained and adjusted unless there was an actual record for at least half of the hour, nor for a day unless there were records for at least half of the hours of the day. There were very few hours and very few days for which this lower limit was approached, only one of the 582 days' records being based on 12 hr, 4 on 15 hr, 2 on 16 hr, 1 on 17 hr, 6 on 18 hr, 3 on 19 hr, 6 on 20 hr, 8 on 21 hr, 14 on 22 hr, and 44 on 23 hr. As is shown in the tables, records for a few days were rejected entirely. Burst totals for the day and daily average values for all the other variables were used in determining the coefficients listed in the tables.

It had become apparent from the reading of the first series of records that in spite of consultation and training, and serious efforts to apply the same criteria, two readers, although they could reproduce their own readings fairly well, were inclined to disagree noticeably in the reading and classification of bursts according to size. An attempt was made, therefore, to have all bursts of the recent series read by a single reader. This was found to be impossible, however, and instead, four readers had to be employed. Dr. Long, who was reader A of the first series and read the records for two-thirds of that series, was reader No. 1 of the later series and the instructor for reader No. 2. Numbers (in the tables) were assigned to the readers in the order in which each received instruction from the next preceding. The first three readers were physicists with considerable experience beyond the Ph.D. degree. Reader No. 4 was a young lady with no training in physics or other science. Unexpectedly great differences in reading the small bursts were found by having the records for a few of the months read by more than one reader. This situation is shown graphically by Fig. 1 which gives the average frequency of bursts in the 1.0 to 1.5 mm range during each month (or portion thereof for October, 1947, and March, 1948) as determined by the reader whose number is designated. Because the breaks representing bursts were so sharp and were practically perpendicular to the time axis, it is presumed that the difficulty must have been one of deciding just where the photographic trace ended and began on either side of the burst. The magnification was perhaps inadequate, also. In order to minimize effects of fatigue, the readers generally did not continue reading for more than two hours at a time.

V. DETERMINATION OF COEFFICIENTS

Assuming linear relations, simple barometric coefficients were determined for each month for the 1-mm bursts of the 1938–1939 series, and partial barometric and (surface) temperature coefficients for the 1-mm bursts and for the CR ionization after correction for all bursts $\geqslant 1$ mm, for the 1947–1949 series, by the method of least squares. For the first series, 1-mm bursts were defined to be those producing deflections of 1 to 1.2 mm of the photographic record, and represented the production of $(2.9 \text{ to } 3.6)\times 10^6$ ion pairs, while the 1-mm bursts of the second series were defined to be those producing 1.0- to 1.5-mm deflection and represented the production of $(1.2 \text{ to } 1.9)\times 10^6$ ion pairs. Taking the average length of path of the burst-producing particles to be 19.1 cm in the chamber, and supposing these to produce 100 ion pairs per cm per atmosphere in the argon, the 1-mm bursts of the second series appear to correspond to the passage of about 31 to 50 particles through the chamber, or to an average flux density of 0.045 to 0.072 particles/cm². Details of the statistical procedure are given in Appendix II.

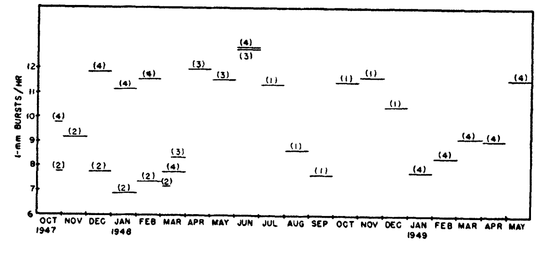

FIG. 1. Monthly average values of frequency of 1-mm bursts. Readers are designated by numbers in parentheses.

VI. DATA AND DISCUSSION

The values of the coefficients obtained in this manner are shown in the tables. Table I shows the simple barometric coefficients, b_{12}, in percent/mm Hg for the 1-mm bursts of the first series for each month, together with the corresponding correlation coefficients and their significance ratios. For one month no correlation was obtained, while positive coefficients were obtained for

TABLE I. Simple regression (b) and correlation (r) coefficients and significance ratios (t) for frequency of 1-mm bursts with respect to barometric pressure for the 1938–1939 series. [The 1-mm bursts of this table represent $(2.9 \text{ to } 3.6)\times 10^6$ ion pairs, while the 1-mm bursts of the 1947–1949 series represent $(1.2 \text{ to } 1.9)\times 10^6$ ion pairs.]

Month	Reader	b_{12} (%/mm)	r_{12}	t_{12}
(1938)				
June	A	−3.2	−0.25	−1.35
July	A	−2.0	−0.18	−0.94
Aug.	A	2.4	0.18	0.94
Sept.	A	0.0	0.00	0.00
Oct.	A	−4.0	−0.48	−2.63
Nov.	A	−1.1	−0.30	−1.62
Dec.	A	−1.2	−0.21	−1.15
(1939)				
Jan.	A	−2.3	−0.42	−2.22
Feb.	A	−2.4	−0.57	−2.91
Mar.	A	−3.5	−0.60	−3.29
Apr.	A	−1.6	−0.23	−1.24
May	A	−3.5	−0.47	−2.49
June	B	−2.7	−0.28	−1.51
July	B	−2.0	−0.24	−1.31
Aug.	B	−2.1	−0.18	−0.97
Sept.	B	1.5	0.22	1.18
Oct.	B	−1.7	−0.38	−2.08
Nov.	B	−4.2	−0.42	−2.26

Average of 18 monthly values of $b_{12} = -1.87$ percent/mm.
Average of 4 values of b_{12} above 2 percent level $= -3.35$ percent/mm.

TABLE II. Partial regression (*b*) and correlation (*r*) coefficients and significance ratios (*t*) for frequency of 1-mm bursts with respect to barometric pressure (12·3) and outdoor temperature (13·2) for individual months.

Month	No. of days	Reader	$b_{12\cdot3}$ (%/mm)	$r_{12\cdot3}$	$t_{12\cdot3}$	$b_{13\cdot2}$ (%/°C)	$r_{13\cdot2}$	$t_{13\cdot2}$
(1947)								
November	26	2	−3.11	−0.552	−2.71	−0.98	−0.226	−1.11
December	30	2	−0.43	−0.103	−0.55	−0.34	−0.100	−0.53
December	30	4*	−0.20	−0.077	−0.41	−1.13	−0.450	−2.38
(1948)								
January	31	2	−2.00	−0.478	−2.57	−1.48	−0.649	−3.50
January	31	4*	−4.39	−0.639	−3.44	−2.76	−0.743	−4.00
February	28	2	−1.47	−0.353	−1.80	−0.69	−0.315	−1.61
February	29	4*	−1.32	−0.515	−2.67	−0.13	−0.110	−0.57
March	31	(2 and 3)	0.83	0.105	0.57	1.49	0.326	1.76
March	31	4*	−1.36	−0.517	−2.78	−0.77	−0.524	−2.82
April	30	3	−1.86	−0.590	−3.12	−0.36	−0.155	−0.82
May	31	3	−1.46	−0.526	−2.83	−1.05	−0.533	−2.87
June	30	3*	−1.03	−0.199	−1.05	−2.53	−0.543	−2.88
June	30	4	−0.26	−0.068	−0.36	−0.14	−0.306	−1.62
July	31	1	−5.79	−0.441	−2.37	−4.37	−0.351	−1.89
August	31	1	1.01	0.120	0.64	−2.93	−0.457	−2.46
September	27	1	−1.53	−0.314	−1.57	0.50	0.116	0.58
October	31	1	−0.35	−0.058	−0.31	−1.73	−0.297	−1.60
November	30	1	−0.44	−0.095	−0.50	0.53	0.172	0.91
December	31	1	−3.27	−0.516	−2.78	−1.49	−0.300	−1.61
(1949)								
January	31	4	−1.03	−0.250	−1.35	−0.51	−0.188	−1.01
February	28	4	−0.80	−0.461	−2.35	−0.05	−0.062	−0.32
March	31	4	−0.97	−0.416	−2.24	0.18	0.107	0.58
April	30	4	−0.99	−0.568	−3.01	−0.48	−0.526	−2.78
May	31	4	−0.39	−0.079	−0.42	1.49	0.355	1.91

* Choosing reader designated by asterisk for months with 2 readers:
average of 19 monthly values of $b_{12\cdot3} = -1.54$ percent/mm;
average of 19 monthly values of $b_{13\cdot2} = -0.98$ percent/°C.
(Average of 19 monthly values of $b_{12} = -1.28$ percent/mm;
average of 19 monthly values of $b_{13} = -0.78$ percent/°C.)
Average of 10 monthly values of $b_{12\cdot3}$ with $t_{12\cdot3}$ above 2 percent level = −2.44 percent/mm;
average of 7 monthly values of $b_{13\cdot2}$ with $t_{13\cdot2}$ above 2 percent level = −1.66 percent/°C.
(Average of 8 monthly values of b_{12} with t_{12} above 2 percent level = −1.58 percent/mm;
average of 5 monthly values of b_{13} with t_{13} above 2 percent level = −1.97 percent/°C.)
The magnitude of the normal *t* employed = 2.33 at the 2 percent level.

two. For them, low significance ratios were obtained. The remaining 15 months provided negative coefficients. The average of all 18 monthly (simple) barometric coefficients is −1.87 percent/mm Hg. Only four of these have significance ratios above the 2 percent level, and these all have quite large negative regression coefficients. The average of these four is −3.35 percent/mm Hg. The earlier report[1] on the barometric coefficient for some of these months includes a discussion of conditions, shows the results of certain manipulations of the data for a couple of the months, and points out the (fair) agreement in magnitude with values obtained by other observers.[2,3] Messerschmidt[11] also found a coefficient of −1 to −2 percent/mm Hg, the latter being emphasized. Hogg[12] found a barometric coefficient of −0.75 percent/mm Hg for a class of bursts with an average frequency of 0.88 per hour.

Table II shows barometric coefficients (partial regression coefficients $b_{12\cdot3}$) and outdoor temperature coefficients (partial regression coefficients $b_{13\cdot2}$) in columns 4 and 7, followed by the corresponding correlation coefficients and their significance ratios, for the frequency of the 1-mm bursts for each of the individual 19 full months of the 1947–1949 series. Column 3 designates the number of the reader, and column 2 gives the number of days for which records were retained by that reader for the month designated in column 1.

It will be noted that there was only one month, August, 1948, for which only a positive barometric coefficient was obtained, and that the correlation coefficient for this month was small with a small significance ratio. Table I shows that August, 1938, also had a positive barometric coefficient with poor correlation, while August, 1939, had a negative barometric coefficient, but with poor correlation. September, 1948, differs from September of 1938 and 1939 in displaying

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[11] W. Messerschmidt, Z. Physik **103**, 27 (1936).
[12] A. R. Hogg, Nature **138**, 77 (1936).

Table III. Partial regression and correlation coefficients and significance ratios as in Table II, but for the longer intervals specified below.

Time interval	$b_{12\cdot 3}$ (%/mm)	$r_{12\cdot 3}$	$t_{12\cdot 3}$	$b_{13\cdot 2}$ (%/°C)	$r_{13\cdot 2}$	$t_{13\cdot 2}$
6 mo.; Nov. '47–Apr. '48	−0.55	−0.299	−3.96	−0.35	−0.143	−1.89
6 mo.; May '48–Oct. '48	−1.54	−0.192	−2.57	−1.32	−0.307	−4.10
6 mo.; Nov. '48–Apr. '49	−0.96	−0.201	−2.69	0.43	0.178	2.38
Average of 6-mo. values	−1.02			−0.41		
18 mo.; Nov. '47–Apr. '49	−0.60	−0.105	−2.43	0.18	0.079	1.84
581 days during 21 Oct. '47 to 31 May '49	−0.64	−0.113	−2.72	0.24	0.105	2.52

a negative barometric coefficient, but the correlation is not very high. While the correlation coefficients and their significance ratios, as well as the regression coefficients, are seen to vary a good deal from month to month, and the disagreement among the readers is apparent, there are 10 months for which significance ratios above the 2 percent level were obtained. To form an average of the monthly values, it seemed proper to choose the values obtained by one or the other of the readers for those months read by two readers. For determining such averages, then, as well as for determining the values listed in Table III, the readings obtained by the reader whose number is marked with an asterisk in column 3 were arbitrarily employed. On this basis, the average of the 19 monthly barometric coefficients is $b_{12\cdot 3} = -1.54$ percent/mm Hg, while the average of the 10 monthly coefficients with $t_{12\cdot 3}$ above the 2 percent level is $b_{12\cdot 3} = -2.44$ percent/mm Hg. At the bottom of the table the corresponding average values of the simple barometric coefficients, b_{12}, are also listed. These averages are seen to be quite comparable to those obtained from the earlier observations, though they are a little smaller.

The temperature coefficients of the burst frequencies listed in column 7 of Table II are also seen to be predominantly negative, although for these there are 4 months for which only positive values were obtained. All these display quite low correlation coefficients and significance ratios except May, 1949, which is near the 5 percent level. In fact, only 7 of the months have significance ratios above the 2 percent level, and these are all negative. Selecting readers as before, the average of the 19 monthly temperature coefficients is $b_{13\cdot 2} = -0.98$ percent/°C; and the average of the 7 monthly values with $t_{13\cdot 2}$ above the 2 percent level is $b_{13\cdot 2} = -1.66$ percent/°C. The corresponding average values of the simple temperature coefficients are also given at the bottom of the table.

Table III shows coefficients corresponding to those in Table II, computed by grouping together all the daily values in each of the successive 6-month intervals designated in the first three rows; those for all 18 of these months for the fourth row; and for the fifth row, all for the 19 months of Table II plus those for the last 11 days of October, 1947. For all these cases negative barometric coefficients are displayed, with all significance ratios above the 2 percent level. The negative barometric coefficients are generally smaller, however, than the averages obtained from the monthly values. The temperature coefficients are rather strikingly different from those of Table II. While negative coefficients are obtained for the first two 6-month intervals, all the other groupings produce positive temperature coefficients. In particular, the third 6-month interval and the entire period of 581 days show positive temperature correlation with significance ratios above the 2 percent level. In contemplating this situation, it should be borne in mind that all the readers were involved in the last case, while the individual monthly values were generally dependent upon a single reader. Also, although the partial correlation procedure is supposed to remove the effect of barometric variations, it seems to the reader that the large corresponding seasonal variations in temperature and barometric pressure may have produced some effect. These variations are shown in Fig. 2, where monthly average values of barometric pressure and temperature are represented. According to information supplied by a geographer, the positive correlation between seasonal variations in barometric pressure and temperature displayed here are quite unusual for an inland station; but a similar relation was observed during the 1938–1939 observations. Perhaps an explanation of the differences between the temperature coefficients of Tables II and III might be found in terms of the differences between variations in the atmospheric temperature at the surface of the earth and at higher levels. Duperier[13] has found a positive meson temperature coefficient of 0.12 percent/°C with respect to temperature of the air layer between 200 and 100 mb (a layer of 4.2 km average depth and 14 km mean height), which he explains in terms of π-meson decay.

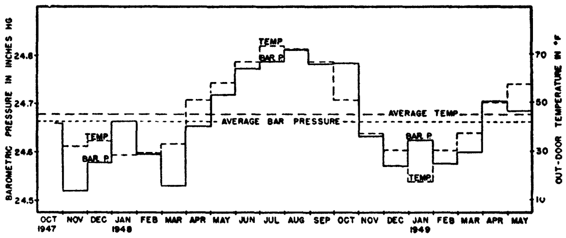

Fig. 2. Monthly average values of barometric pressure and outdoor temperature.

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[13] A. Duperier, Proc. Phys. Soc. (London) **A62**, 684 (1949).

TABLE IV. Partial regression and correlation coefficients and significance ratios as in Table II, for the cosmic-ray ionization after correction for all bursts producing deflections of 1 mm or more on the photographic record.

Month	No. of days	Reader	$b_{12\cdot3}$ (%/mm)	$r_{12\cdot3}$	$t_{12\cdot3}$	$b_{13\cdot2}$ (%/°C)	$r_{13\cdot2}$	$t_{13\cdot2}$
(1947)								
November	26	2	−0.065	−0.518	−2.54	−0.070	−0.588	−2.88
December	30	2*[b]	−0.141	−0.882	−4.67	−0.014	−0.222	−1.18
December	30	4	−0.143	−0.823	−4.35	−0.009	−0.115	−0.61
(1948)								
January	31	2*	−0.151	−0.768	−4.14	−0.052	−0.661	−3.56
January	31	4	−0.127	−0.675	−3.64	−0.038	−0.498	−2.68
February	28	2	−0.137	−0.823	−4.20	−0.023	−0.416	−2.12
February	29	4*	−0.139	−0.805	−4.18	−0.028	−0.461	−2.39
March	31	(2 and 3)*	−0.144	−0.778	−4.19	−0.051	−0.628	−3.38
March	31	4	−0.127	−0.622	−3.35	−0.029	−0.317	−1.71
April	30	3	−0.144	−0.939	−4.97	−0.044	−0.675	−3.57
May	31	3	−0.202	−0.707	−3.81	−0.037	−0.249	−1.34
June	30	3	−0.172	−0.850	−4.50	0.008	0.128	0.68
June	30	4*	−0.174	−0.900	−4.76	−0.015	−0.225	−1.19
July	31	(1 and 3)*	−0.144	−0.687	−3.70	−0.067	−0.410	−2.21
July	31	1	−0.084	−0.279	−1.50	0.011	0.037	0.20
August	31	1	−0.175	−0.697	−3.75	−0.017	−0.137	−0.74
September	27	1	−0.132	−0.742	−3.71	−0.062	−0.492	−2.46
October	31	1	−0.220	−0.916	−4.93	−0.045	−0.451	−2.43
November	30	1	−0.123	−0.894	−4.73	−0.047	−0.757	−4.01
December	31	1	−0.178	−0.778	−4.19	−0.032	−0.263	−1.42
(1949)								
January[a]	29	4	−0.159	−0.883	−4.58	−0.039	−0.560	−2.91
February	28	4	−0.179	−0.909	−4.63	−0.039	−0.713	−3.64
March	31	4	−0.184	−0.953	−5.13	−0.016	−0.335	−1.80
April	30	4	−0.136	−0.601	−3.18	−0.027	−0.265	−1.40
May	31	4	−0.140	−0.667	−3.59	−0.027	−0.210	−1.13
All	581		−0.174	−0.751	−18.06	−0.056	−0.673	−16.19
Average of 19 monthly[b] values			−0.154			−0.038		
Average of 10 monthly[b] $b_{13\cdot2}$ with $t_{13\cdot2}$ above 2 percent level						−0.048		

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[a] Two days of high magnetic disturbance omitted in Jan., 1949.

[b] When 2 readers for same month, values by starred reader chosen.

Table IV contains coefficients for the CR ionization currents of the 1947–1949 series after correction for all bursts $\geqslant 1$ mm, corresponding to the coefficients for the 1-mm bursts given in Table II. In this, all the barometric coefficients given in column 4 are seen to be negative, and there is much better agreement among the different readers. The correlation coefficients are generally high, and every month displays a significance ratio for the barometric correlation above the 1 percent level except the first, and it is nearly at this level. Choosing values obtained by the reader designated by the asterisk for months with two readers, the average of the monthly barometric coefficients shown in the table is $b_{12\cdot3}=-0.154$ percent/mm Hg. The corresponding average of the simple regression coefficients is $b_{12}=-0.145$ percent/mm Hg, precisely the same as for the 18 months of the 1938–1939 series. Grouping together the data for the last 11 days of October, 1947, as well as for those of all the months shown in the table, the barometric coefficient computed for the 581 days is $b_{12\cdot3}=-0.174$ percent/mm Hg with the correlation coefficient $r_{12\cdot3}=-0.75$ and the large significance ratio $t_{12\cdot3}=-18.06$.

The temperature coefficients in column 7 are seen to be more consistently negative than in the case of the 1-mm bursts, each month displaying a negative coefficient according to at least one reader. The average of the monthly temperature coefficients (using values of the reader indicated by an asterisk in the case of two readers) is $b_{13\cdot2}=-0.038$ percent/°C, while the average of the 10 monthly values with $t_{13\cdot2}$ above the 2 percent level is $b_{13\cdot2}=-0.048$ percent/°C. The temperature coefficient obtained by grouping together the data for all the 581 days specified above is $b_{13\cdot2}=-0.056$ percent/°C with the correlation coefficient $r_{13\cdot2}=-0.67$ and the large significance ratio $t_{13\cdot2}=-16.19$. This is a far different situation from that found for the 1-mm bursts.

VII. COMPARISON WITH OTHERS AND FURTHER DISCUSSION

The comparison of the coefficients for the burst-corrected CR ionization with those obtained by other experimenters may be introduced by reference to a theoretical explanation of the temperature effect. Blackett[14] assumed the effect to be dependent upon meson decay, and making certain reasonable assumptions regarding the place of origin, energy, and mean life of the mesons, computed temperature coefficients of −0.16 to −0.20 percent/°C in good agreement with the value −0.18 percent/°C found by Compton and Turner,[15] and predicted the latitude effect in the temperature coefficient later found by Gill.[16] Gill found that the temperature coefficient increased with latitude, attaining its highest numerical value of −0.25 percent/°C for latitudes above 40° N and S.

Recently Duperier,[17] following Blackett,[14] has had remarkable success in explaining the differences among the temperature coefficients measured by various excellent experimenters, as well as the seasonal variations in the temperature coefficient observed by some of them, and the 12-monthly wave obtained by Forbush,[18] solely on the basis of meson decay. Duperier pointed out that Hess,[19] *et al.*, and Hogg[20] had employed daily average values in determining their average temperature coefficients of −0.09 to −0.11 percent/°C in Austria and Australia, respectively, with seasonal variations consisting of a ratio of about 2 in the first instance and 1.6 in the second, for the ratio of the barometric coefficient for winter months to that for summer months. (Hess found that the temperature coefficient changed only from −0.09 percent/°C at 2300 m altitude to −0.11 percent/°C at 600 m, both at 48.4° N geomagnetic latitude.) Duperier further pointed out that Compton and Turner,[15] Gill,[16] Schonland,[21] *et al.*, and Clay and Bruins[22] had used monthly or seasonal means in determining their temperature coefficients, and that the average of the coefficients determined by them, −0.18 percent/°C, was about twice that obtained by the first group (though the Schonland value, −0.12 percent/°C at 32.7° S geomagnetic latitude, was about equal to that of the first group).

Duperier explained that on the hypothesis of the instability of the meson, the use of daily means results in a smaller value of the (surface) temperature coefficient on account of the lag in the warming of the atmosphere relatively to the warming of the ground. Assuming that the mesons originate chiefly at the 75-mm Hg pressure level (at a mean height of 16 km; von Roka,[23] in his interesting explanation of the 27-day recurrences in CR intensity and bursts, considers that about $\frac{1}{3}$ of the mesons originate at a height between 25 and 50 km) Duperier obtained $L=18.6$ km for the mean range of the mesons, and upon the basis of the temperature-dependent variations of the height of the atmospheric layer presumed to provide the principal source of the unstable mesons, he deduced the value −0.10 percent/°C for the average temperature coefficient based upon daily averages, with a seasonal variation yielding 1.6 for the ratio of the temperature coefficient for winter months to that for summer months. He also deduced −0.24 percent/°C for the temperature coefficient based on monthly averages. His 12-monthly wave deduced on this basis agreed well in both amplitude and phase with that found by Forbush. Kidnapillai[24] has deduced a barometric coefficient of magnitude 0.316 percent/mm Hg on the basis of meson decay.

Because the temperature coefficients listed in Table IV were obtained from daily average values of the variables, they should, according to Duperier, be comparable to those obtained by Hess and by Hogg. It is seen, however, that the $b_{13\cdot 2}=-0.056$ percent/°C listed for all 581 days is only about half as great as the −0.10 percent/°C deduced by Duperier and measured by these experimenters, which in turn is only about half as great as the values obtained theoretically by Duperier and experimentally by the second group, for the temperature coefficient based on monthly averages. Moreover, Hogg[20] obtained $b_{12\cdot 3}=-0.275$ percent/mm Hg for the average barometric coefficient during a period of five years. Hess[25] obtained an average barometric coefficient of about −0.367 percent/mm Hg in Austria, with individual 10-day values fluctuating between about 0.7 and 1.5 times this value. It is seen that the value $b_{12\cdot 3}=-0.174$ percent/mm Hg listed for all 581 days in Table IV is also only about half as great as those barometric coefficients.

The disagreement of the coefficients presented here with the values obtained theoretically and experimentally by the same means by others (and at comparable latitude and altitude in the case of Hess) appears to require explanation. The simplest explanation appears to be the possibility either of an error in calibration or of radioactive contamination of the chamber or other local radiation which may have caused us to use for the average burst-corrected CR ionization a value approximately double the correct value. The probability of an error of such magnitude seems exceedingly slight for a combination of reasons. As mentioned before, the averages of the (simple)

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[14] P. M. S. Blackett, Phys. Rev. **54**, 973 (1938).

[15] A. H. Compton and R. N. Turner, Phys. Rev. **52**, 799 (1937).

[16] P. S. Gill, Phys. Rev. **55**, 1151 (1939).

[17] A. Duperier, Proc. Phys. Soc. (London) **A61**, 34 (1948).

[18] S. E. Forbush, Phys. Rev. **54**, 975 (1938).

[19] V. F. Hess, Phys. Rev. **57**, 781 (1940).

[20] A. R. Hogg, Proc. Roy. Soc. (London) **A192**, 128 (1947); the valuable comprehensive report by Hogg, Memoir No. 10 (No. 5 of Vol. II), Memoirs of the Commonwealth Observatory, July, 1949, was not received by the writer until after this paper had been submitted for publication.

[21] Schonland, Delatizky, and Gaskell, Terr. Mag. **42**, 137 (1937).

[22] J. Clay and E. M. Bruins, Revs. Modern Phys. **11**, 158 (1939).

[23] E. G. v. Roka, Naturwissenschaften **36**, 24 (1949).

[24] M. Kidnapillai, Phys. Rev. **72**, 518 (1947).

[25] From a personal letter by Dr. Victor F. Hess.

barometric coefficients determined in the present series and in that of a decade earlier agreed precisely. Independent calibrations of the apparatus by Long[8] and by Whaley[6] and the writer during the earlier series agreed within 2 percent, and it appeared that the experimental error should not be greater than this. The average value of 38.2 ion-pairs cc^{-1} sec^{-1} for the CR ionization during the first 18-month series of recordings is comparable to the values 45.4 and 42.6 (corrected only for very large bursts) obtained in the same chamber with air at the same pressure during still earlier visual measurements[4] of short duration, with a 2-in. lead shield and with a 5.5- to 6-ft water shield in addition to the lead, at another location in the same building. Those visual measurements were made by manual application of varying potentials to a compensating condenser which contained no radioactive material, and depended upon a wholly independent calibration, of course. During these visual measurements the value 1.45 ion-pairs cc^{-1} sec^{-1} was obtained with both shields with air in the chamber at a pressure of 0.82 atmos, which showed that the chamber was remarkably free from radioactive contamination; and it has been protected carefully ever since. For such reasons, it appears to the writer that the value of 39 pairs of ions cc^{-1} sec^{-1} assumed for the average burst-corrected CR ionization current in the present series is probably accurate to within about 2 percent, that it is very unlikely to be in error by as much as 5 percent, and that an error of the order of 50 percent is almost unthinkable. Accuracy of the computations is believed to have been assured by having them all performed twice.

The comparison of the coefficients listed in Table IV with those obtained by other observers may be presented in a manner considerably more favorable than that adopted above. For instance, Hogg[20] found monthly mean values of the barometric coefficient to vary from -0.135 to -0.412 percent/mm Hg, the lower value being less than our $b_{12\cdot 3}$ for 581 days. Also, his monthly mean values of the temperature coefficient varied from -0.011 to -0.286 percent/°C for the negative values; and two months yielded positive coefficients. The lower negative value is seen to be considerably less than our $b_{13\cdot 2}$ for 581 days, and it will be recalled that each of the 19 months yielded a negative coefficient according to at least one observer. Moreover, for the entire year of 1939 Hogg obtained an average $b_{12\cdot 3}=-0.239$ percent/mm Hg and an average $b_{13\cdot 2}=-0.085$ percent/°C, values much closer to our 581-day values than were his averages for five years. Also, Hess[19] obtained the value $b_{13\cdot 2}=-0.055$ percent/°C for the summer months, a value quite comparable to ours which displayed no seasonal effect. Hess, *et al.*, found that the use of hourly values resulted in positive temperature coefficients during late summer. Schonland,[21] *et al.*, obtained a barometric coefficient of -0.216 percent/mm Hg at Capetown and mention that Messerschmidt[26] obtained the value -0.178 percent/mm Hg at Halle and that Steinke[2] obtained the value -0.20 percent/mm Hg at Königsberg, all values more nearly comparable to our $b_{12\cdot 3}=-0.174$ percent/mm Hg for 581 days, and all obtained with comparable lead shields. Forbush[27] in 1937 obtained a barometric coefficient of -0.236 percent/mm Hg and concluded that no atmospheric temperature coefficient as great as ± 0.024 percent/°C exists. Clay and Bruins[22] obtained a barometric coefficient of -0.64 percent/mm Hg at Amsterdam, which is considerably larger than the values mentioned above. Using G-M tubes in vertical array, Hess,[28] *et al.*, obtained a barometric coefficient of -0.218 percent/mm Hg at New York, and temperature coefficients of -0.033 percent/°C in summer and -0.155 percent/°C in winter. Forró[29] recently found a positive temperature coefficient of 0.74 percent/°C under 1000-m water equivalent in a coal mine near Budapest, and concluded that there was no dependence upon barometric pressure there.

In view of the dependence upon the use of daily averages or monthly averages in the computation of the temperature coefficients according to Duperier, new barometric and temperature coefficients were computed on the basis of monthly averages for the burst-corrected CR ionization for the 19 full months of the present series. On this basis the following coefficients were obtained: $b_{12\cdot 3}=-0.199$ percent/mm Hg, $r_{12\cdot 3}=-0.505$, $t_{12\cdot 3}=-2.08$, and $b_{13\cdot 2}=-0.057$ percent/°C, $r_{13\cdot 2}=-0.557$, $t_{13\cdot 2}=-2.30$. Remarkably, the regression coefficients thus obtained are only a little higher than those obtained on the basis of the 581 daily averages as given in Table IV, and the temperature coefficients are almost identical. This leads us to wonder whether one ought not to compare the coefficients obtained by the two methods of averaging, from treatment of the data of a single experimenter rather than by employment of data obtained by two groups of experimenters as Duperier has done; possibly the situation he has emphasized could account in part for the differences between the barometric coefficients of the bursts shown in Tables II and III. In computing the partial coefficients based on monthly averages, an interesting situation regarding the simple coefficients was observed. These are $b_{12}=-0.394$ percent/mm Hg, $r_{12}=-0.879$, $t_{12}=-3.73$; $b_{13}=-0.099$ percent/°C, $r_{13}=-0.888$, $t_{13}=-3.77$; $r_{23}=0.853$, $t_{23}=3.62$. The simple barometric and temperature coefficients are seen to be closely comparable to some of the larger coefficients obtained by others as discussed above. Also, the high (simple) positive correlation between the barometric pressure and atmospheric temperature on a seasonal (monthly averages) basis serves to produce considerably lower coefficients for the partial correlation

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[26] W. Messerschmidt and W. Pforte, Z. Physik **73**, 677 (1932).

[27] S. E. Forbush, Terr. Mag. **42**, 1 (1937).

[28] Altmann, Walker, and Hess, Phys. Rev. **58**, 1011 (1940).

[29] M. Forró, Phys. Rev. **72**, 868 (1947).

of the CR intensity relative to barometric pressure and to temperature than is indicated by the high, negative, individual (simple) coefficients relating CR intensity to these variables.

Comparison of the values in Tables II and IV shows that both the barometric and the temperature coefficients for the 1-mm bursts are of a higher order of magnitude than the corresponding coefficients for the burst-corrected ionization. Moreover, the reversal of sign of the temperature coefficient for the 1-mm bursts for the full period of observation (Table III) as differentiated from the coefficients for most of the individual months, has no counterpart in the burst-corrected ionization. These observations provide further confirmation of the evidence provided earlier,[1] that the small bursts and the burst-corrected CR ionization are produced by different types of penetrating radiation.

VIII. MASS ABSORPTION COEFFICIENTS

Estimates of the mass absorption coefficients of the different radiations presumed to be responsible for the small bursts and for the burst-corrected CR ionization can be made. Some years ago the writer[4] employed the chamber described here, shielded with 5.1-cm Pb, to measure by visual observations the absorption produced by a few feet of water in a large tank. Corrections were made only for large bursts observed visually, of course. Assuming exponential absorption, $I=I_0e^{-\mu x}$, limiting values of $\mu=0.0010$ and $\mu=0.0028$ cm^{-1} H_2O were obtained on the respective assumptions that the radiation was all incident vertically, and that it was incident uniformly from all directions above the horizontal. Because of the difficulty caused by the irregular shielding afforded by the heavy-walled building (the chamber was then located at a different place in the same basement where it is now located) it is not easy to make a satisfactory estimate of the actual distribution of the incoming radiation. On the assumption that the actual distribution is represented somewhat better by the first limit than by the second, we assign the first twice the weight of the second for the present purpose to obtain an average $\mu=0.0016$ cm^{-1} H_2O. This corresponds to a mass absorption coefficient or mean range or mean free path $\lambda=1/\mu=625$ g/cm^2.

An estimate may also be made from the barometric coefficient. Referring again to visual observations[30] made some time ago, a barometric coefficient of $b_{12}=-0.21$ percent/mm Hg was observed during a period of 15 days with the chamber shielded by a 5.5–6 ft shield of water. Taking account of the density of Hg and the fact that the coefficient is here expressed in percent, we obtain from this the value $\lambda=136/-b_{12}=648$ g/cm^2. Turning to Table IV of the present work, and using the multiple regression coefficient $b_{12\cdot3}=-0.174$ percent/mm Hg for all 581 days, we obtain $\lambda=136/-b_{12\cdot3}=782$ g/cm^2. The corresponding simple barometric coefficient (not listed in Table IV) for all 581 days, $b_{12}=-0.215$ percent/mm Hg yields $\lambda=633$ g/cm^2. Hogg[20] obtained a value for $\mu=0.0021$ from the barometric effect, and 0.0015 directly from absorption in lead. These values correspond to $\lambda=1/\mu=476$ and 667 g/cm^2, respectively. From their difference he deduced the value 2.8 μsec for the rest life of the meson.

Turning to Table II for the 1-mm bursts, and using $b_{12\cdot3}=-1.54$ percent/mm Hg (average of 19 monthly values) we obtain $\lambda=88$ g/cm^2 for the burst-producing radiation. Using $b_{12\cdot3}=-2.44$ percent/mm Hg (average of 10 monthly values with $t_{12\cdot3}$ above the 2 percent level) we obtain $\lambda=56$ g/cm^2. Use of the barometric coefficient given in Table III for all 581 days yields $\lambda=213$ g/cm^2; but it seems that much less confidence should be placed in this value for reasons mentioned above, particularly because it depends upon all four readers.

These values do not agree well with those obtained by Lewis[31] by shielding low pressure chambers with shields of Pb, Fe, and Al. According to him, "The mean free path changes continuously from 390 gm/cm^2 for bursts greater than 7×10^5 ion pairs to 190 gm/cm^2 for bursts greater than 2.3×10^6 ion pairs. Apparently, the absorption length approaches the geometrical one as the energy of the burst increases." Using their barometric coefficient, Jánossy[32] found $\lambda=113$ g/cm^2 for penetrating showers.

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APPENDIX I. APPARATUS

The principal features of the high pressure CR ionization chamber were given in a paper[4] in 1931. Figure 1 of that paper is a photograph of the chamber mounted at the center of the 14-ft water tank where it was then used, with part of its lead shield in position. Figure 3 of that paper represents a longitudinal section of the chamber which shows the wall thickness and guard system, but a different central electrode from that currently employed. Figure 1 of a later paper[5] shows a very thin-walled sphere mounted concentrically with the walls of the high-pressure chamber. In that diagram the thin central sphere is shown connected to the outer wall through its thin-walled supporting tube. For the 1938–1939 and the current measurements, the

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[30] Broxon, Merideth, and Strait, Phys. Rev. 43, 687 (1933).

[31] L. G. Lewis, Proceedings of the Echo Lake Cosmic Ray Symposium (Office of Naval Research), 244 (1949), unpublished.

[32] L. Jánossy, *Cosmic Rays* (Oxford University Press, 1948), p. 358.

lower end of the supporting tube of this central sphere was modified to fit into the central cone and thereby form the collecting electrode of the central system, the very small collecting electrode and its accompanying guard extension, as shown in Fig. 1, being removed. The thin sphere was supported from below as shown.

Following are the dimensions. The spherical cavity was 29.77 cm in diameter cut concentrically from a cylindrical, nickel-steel ingot 38.42 cm in diameter and 44.13 cm long. The thin-walled spherical collecting electrode had an outer diameter of 9.45 cm and a wall thickness of 0.015 cm, and weighed 33.3 g. Its supporting tube had an outer diameter of 1.35 cm and a wall thickness of 0.020 cm. The volume from which ions were collected was thus approximately 13.3 liters.

As used in the 1938–1939 and the current series of measurements, the chamber was mounted on three Bakelite legs on a brick pier with a stone top, built from the ground in the basement of a rather large building a few feet from one of its thick (30 in.) outer stone walls. The chamber was shielded with 10.2 cm of lead beneath, and 12.7 cm of lead around its sides and over the top. The lead shield was cast from old telephone-cable sheaths. An oil-cloth cover was placed over the lead shield to decrease circulation of the atmosphere through it. Whaley[6] has estimated that the shielding afforded by the building, though irregular, was roughly equivalent to 39 cm Pb. The writer[1] estimated that the shielding by the building would probably amount to some 15 cm Pb for any direction and much more than 40 cm Pb for certain directions, and pointed out that the shielding provided by the chamber walls varied from a little over 7 cm of steel for vertical rays through the center, through a maximum of over 14 cm for central rays at about 42° zenith angle to a minimum of about 4 cm for horizontal central rays. Earlier experiments[4,5,7] with the chamber at pressures extending to 0.8 atmos and various shields have shown the CR ionization chamber to be remarkably free from radioactive contamination.

As usual, the CR ionization current was nearly compensated, on the average, by a steady, contrary ionization current produced in an auxiliary chamber or compensating condenser by radioactive material. While the steady compensating current did not provide overcompensation for the total CR current in the argon-filled chamber for more than a very few days during the late summer and fall, it did provide overcompensation of the CR current after correction for bursts, for a majority of days during 5 of the months of the present series, although the CR current was generally undercompensated. The auxiliary chamber was a sealed, cylindrical air condenser. The collecting electrode in this was a well guarded cylinder of 15.4 cm length and 6.99 cm o.d. separated by a radial distance of 1.43 cm from both inner and outer coaxial cylinders at high potential. Ions were produced in it by gamma-rays from a sealed capsule containing 1.15 g of a Ra Br concentrate with a content of about 2 μg of Ra located on the axis of the condenser in a special receptacle. To diminish further the production of ions in the thick-walled, spherical, CR ionization chamber, an additional lead plate 7.6 cm thick (5.1 cm for the 1938–1939 series) was placed between the CR chamber and the compensating condenser. The CR chamber was thus shielded from the Ra gamma-rays by at least 20.3 cm Pb and the thick chamber wall. During the 1938–1939 series, positive ions were collected on the central system in the high pressure chamber, while the opposite was true during the 1947–1949 series.

The measuring instrument was a quadrant (Compton-type) electrometer of small capacity. The period of its vane was 6 sec (10 sec in 1938–1939) for a complete oscillation, or 1.5 sec for a ballistic throw. The CR records were obtained by reflecting a beam of light from the mirror on the electrometer vane, onto an 8-in.×20-in. sheet of Kodabromide F2 photographic paper on a drum which rotated once in 25 hr. The electrometer sensitivity was approximately 0.62 mm/mv for the recent observations, about 2.5 times the sensitivity used a decade earlier. The scale was very nearly linear.

In order to apply appropriate potentials and compensate for possible potential fluctuations, the ionization chambers and the electrometer were connected with two wire-wound resistors of approximately 2 and 0.5 megohms, respectively, in a balanced, capacitance-resistance bridge arrangement resembling that represented by Fig. 2 of reference 4. This provided 660 v across the spherical CR chamber and 160 v across the auxiliary chamber. Guard tubes for connecting wires were kept small and short. Long[8] found that the "dead" volume inside the guard system around connecting wires was about 175 cc in 1938–1939. This was increased by an estimated 5 cc during later modification.

Two special keys of the platinum point-to-plane-contact type were incorporated for automatic grounding of the central system and for calibration of the electrometer. The central system was insulated with amber throughout. Amber, incidentally, was the most satisfactory of the insulators tried, including the best polystyrene available. Provision was made for introducing P_2O_5 at three places to maintain dryness of the air in the guard system and of the insulators of the central system.

All the apparatus described above (apart from the light source and rotating drum) and the super-heavy-duty Burgess batteries which supplied the ion collecting potential and electrometer vane potential, were located on the pier and were surrounded by an insulating box containing a two-inch thickness of rock wool. The temperature of the room was controlled by thermostats regulating steam and electric heaters to within about 1°C, the average being 25°C during the recent series. Because of its mass and that of its lead shield, it is presumed that the temperature of the CR ionization chamber was much more nearly constant. In addition to that mentioned above, three beakers of P_2O_5 were maintained inside the insulating box.

For the 1938–1939 measurements the CR ionization chamber was filled with dry air at about 160 atmos. For the 1947–1949 measurements, it was filled with argon at 20.2 atmospheres at 25°C. According to the Linde Air Products Company, which supplied the argon, it was 99.8 percent pure, with impurities consisting of 0.2 percent nitrogen, and other impurities (consisting of oxygen, hydrogen, and carbon dioxide) not exceeding 0.01 percent. The chamber was washed upon filling, by successive insertion and release of the argon, until impurities due to the gas previously in the bomb must have been reduced far below those in the argon supplied. The auxiliary chamber was filled with dry air at the local atmospheric pressure of 62.8 cm Hg, 26°C, and sealed.

APPENDIX II. STATISTICAL PROCEDURE

In order to make quite clear what statistical procedure was employed in obtaining the coefficients listed in the tables, the formulas used in computing these are included. If x_1 represents the total number of 1-mm bursts in a day, for instance, x_2 the average barometric pressure, and x_3 the average outdoor temperature for that day (or variations of these from arbitrary values), then it is assumed that $x_1=a_1+b_{12\cdot3}x_2+b_{13\cdot2}x_3$, where $b_{12\cdot3}$ and $b_{13\cdot2}$ are the partial regression coefficients given by $b_{12\cdot3}=(b_{12}-b_{13}b_{32})/(1-b_{23}b_{32})$, etc., in terms of the simple regression coefficients, b_{12}, etc., given by equations of the form $b_{12}=[N\Sigma x_1x_2-\Sigma x_1\Sigma x_2]/[N\Sigma x_2^2-(\Sigma x_2)^2]$, where N is the number of days. The partial correlation coefficients are represented by relations of the form $r_{12\cdot3}=(r_{12}-r_{13}r_{32})/[(1-r_{13}^2)(1-r_{32}^2)]^{\frac{1}{2}}$ in terms of the simple correlation coefficients, r_{12}, etc., which are expressed in terms of the simple regression coefficients by equations of the form $r_{12}=(b_{12}b_{21})^{\frac{1}{2}}=r_{21}$, the correlation coefficient being assigned the same sign as the corresponding regression coefficient. The significance ratio (t) corresponding to any correlation coefficient is defined to be the ratio of the correlation coefficient to the standard deviation for no correlation. Thus, $t_{12}=r_{12}(N-1)^{\frac{1}{2}}$ and $t_{12\cdot3}=r_{12\cdot3}(N-2)^{\frac{1}{2}}$. $t=2.58$ at the 1 percent level. That is, a value of $t=2.58$ indicates that there is only one chance in a hundred that the correlation is fortuitous. Similarly, $t=2.33$ at the 2 percent level, 1.96 at the 5 percent level, 1.64 at the 10 percent level, 0.67 at the 50 percent level, etc. It is understood that some statisticians regard a correlation as worthy of serious consideration if its corresponding t is at the 5 percent level or higher.