The Radial Gradient of Interplanetary Radiation Measured by Mariners 4 and 5*

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ABSTRACT

The University of Iowa detector package on the Mariner 4 spacecraft, which was launched on a Mars-bound trajectory on 28 November 1964, includes a shielded GM tube (detector C) whose threshold is about 50 to 55 MeV/nucleon for proton and alpha particles. By comparing the counting rate of detector C to that of a similar earth-orbiting GM tube on the IMP-OGO series of spacecrafts we find the following:

(a) As the difference in heliocentric longitude between the two spacecraft increases, there appear differences in the time and/or space development of a Forbush decrease. We estimate that the Forbush decrease may be confined to a region of dimensions as small as 0.5 x 0.7 A.U.

(b) The gradient of particles in the interplanetary medium with energies above the detector energy threshold is directed towards the sun and has magnitude of $(15 \pm 1)\%$/A.U. during the solar minimum period of 1964-1965.

(c) Additional data from the Venus-bound Mariner 5 spacecraft and the Mariner 4 and IMP-OGO spacecrafts during the latter part of 1967 show that the gradient ranged from -24 to -29%/A.U.

(d) Based on the above results, it is shown that the interplanetary flux of particles of $E \geqslant 50$ MeV/nucleon must in part be of solar origin.

(e) It is argued that the gradient of galactic cosmic radiation of $E \sim 50$ MeV/nucleon cannot be measured even at the time of solar minimum.

I. INTRODUCTION

The magnitude and direction of the gradient of cosmic rays in the interplanetary medium during various times of the solar activity cycle is of importance to any modulation theory of cosmic rays. The current ideas may be summarized as follows:

(1) The existence of modulation of cosmic rays implies a gradient in the intensity as a function of radial distance from the sun.

(2) The magnitude of the gradient should vary with the level of solar activity and should be largest at times of greatest cosmic ray modulation at earth.

(3) In the absence of appreciable solar particle production, the gradient should be positive, that is, the intensity should increase as one moves outward from the sun.

(4) During solar activity minimum, it is possible that the cosmic ray intensity observed at the earth is the unmodulated intensity as it exists in the nearby interstellar medium.

In particular, following Parker's [1963] diffusion-convection model one has that the density (and assuming isotropy, the intensity) of particles at $\underline{t}$ is given by

$$\Phi(R,\beta,r) = \Phi(R,\beta,\infty) \cdot \exp\left[-\int_r^L dr' \frac{w(r')}{D(r',\beta,R)}\right] \tag{1}$$

where

Φ = omnidirectional intensity of cosmic rays

w = solar wind velocity

D = diffusion coefficient

R = particle rigidity

$c\beta$ = particle velocity

L = radius of modulating region

r = heliocentric radial distance .

Equation (1) was obtained by integrating the equation

$$-D \frac{d\Phi}{dr} + w\Phi = 0$$

from which we obtain the expression for the gradient, namely

$$\frac{d\Phi}{dr} = \frac{w}{D} \Phi \, . \tag{2}$$

From Eq. (2) we observe that a measurement of the gradient, coupled with the knowledge of the solar wind velocity and the absolute flux of cosmic rays, allows one to unambiguously evaluate the diffusion coefficient D.

Several experiments with interplanetary spacecrafts have been carried out in the past few years in attempts to measure the cosmic ray gradient. The results of these measurements have been summarized by Anderson [1968]. It is evident from Anderson's Table I that the measurements are uncertain by large percentages and are often in conflict with each other. In particular, the measurements obtained using the Mariner 4 spacecraft by O'Gallagher and Simpson [1967], Krimigis [1968], and Anderson [1968] are in direct conflict with each other.

It is the purpose of the present paper to extend the analysis of the Mariner 4 data presented by Krimigis [1968] to protons and alpha particles of energy $\geqslant$ 50 MeV/nucleon. The previous work related to the gradient of protons of $E \geqslant 430$ MeV. The analysis makes use of the earth-orbiting Goddard Space Flight Center IMP-OGO monitor as a reference detector [Balasubrahmanyan et al., 1967], which has a similar threshold ($E \geqslant 50$ MeV/nucleon) to the University of Iowa Mariner 4 detector. Further we present additional data from Mariners 4 and 5 taken during the summer of 1967 which support the conclusions derived from the analysis of the Mariner 4 data.

The primary result of this analysis shows that the integral gradient for protons and alpha particles of $E \geqslant 50$ MeV/nucleon averaged over the period 28 November 1964 to 30 September 1965 is -15% per astronomical unit (A.U.), a result which is in direct conflict with the results of O'Gallagher [1967] and, to a lesser extent, of Anderson [1968].

II. DESCRIPTION OF THE DETECTOR

The University of Iowa package of particle-detectors on Mariner 4 has previously been described in detail [Van Allen and Krimigis, 1965; Krimigis and Armstrong, 1966; Krimigis and Van Allen, 1967]. Briefly, it consists in part of three end-window-type GM tubes having electron energy thresholds of 40 keV (detector B), 45 keV (detector A), and 150 keV (detector C) for particles entering through their collimators. The corresponding proton energy thresholds are 0.55, 0.67, and 3.1 MeV, respectively. Their omnidirectional characteristics are essentially identical with an effective threshold of ~ 55 MeV for protons. In addition to the GM tubes, there is a thin (~ 35 microns) surface barrier solid-state detector responding to protons in the energy ranges $0.50 \leq E_p \leq 11$ MeV (detector D_1) and $0.88 \leq E_p \leq 4$ MeV (detector D_2) and insensitive to electrons of any energy. Each of the five detectors has a conical collimator with a full vertex angle of 60°.

In the present work, we are principally concerned with the data obtained from detector C. The front window of this detector is shielded by ~ 20 mg/cm^2 of aluminum, which determines the aforementioned directional energy thresholds. For the purposes of this paper we consider that the counting rate of detector C is due exclusively to particles penetrating the walls of the counter. This assumption is justified on the following grounds: (a) The effective window area represents only ~ 2% of the total area of the detector, and the window solid angle represents ~ 6% of the total solid angle. (b) By using detectors D_1 and D_2 it is possible to exclude from the data periods during which there exists a finite flux of protons $E_p \geqslant 3.1$ MeV. It is noted that the background counting rate of detector D_1 [Krimigis and Van Allen, 1966] is an order of magnitude below that of C, so that D_1 is an extremely sensitive indicator of the presence of protons $E_p \geqslant 3.1$ MeV.

III. EXPERIMENTAL DETAILS

A. Mariner 4 Detector

Data from detector C were accumulated for 11.25 seconds and read out every 101 seconds from 28 November 1964 to 3 January 1965; commencing on 3 January 1965 data were accumulated for 45 seconds and read out every 403.2 seconds until 30 September 1965. The total number of counts for a given day was ~ 6000 and on the assumption of a Poisson distribution, the standard deviation of the average is 1.3%. In order to improve the statistical uncertainty we have computed five-day averages of the counting rate. Those averages are used throughout this paper and their statistical uncertainty is ~ 0.6%.

B. Monitor Detector

A measurement of the heliocentric dependence of the intensity of cosmic rays requires that two identical detectors perform simultaneous measurements at a fixed and a changing heliocentric radial distance, so that possible time variations may be separated from spatial variations. Fortunately, an instrument very similar to the Mariner 4 detector was in orbit around the earth so that such a comparison can be made. The reference detector is the one flown by the Goddard Space Flight Center on the IMP-OGO series of spacecraft, with an energy threshold similar to that of detector C ($E \geqslant 50$ MeV/nucleon [Balasurbahmanyan et al., 1965; Balasubrahmanyan et al., 1967]). We have used the counting rate of the IMP-OGO monitor (kindly made available to us by Dr. Balasubrahmanyan) as an indicator of the cosmic ray intensity in the vicinity of the earth and compared it to the counting rate of the Mariner 4 detector in order to evaluate the spatial dependence of the intensity of cosmic radiation.

The previous analysis by Krimigis [1968] had used the Deep River neutron monitor as the reference detector and an upper limit of 3% per A.U. was established for the integral gradient for protons of $E_p \geqslant 430$ MeV. Use of the IMP-OGO monitor has allowed us to make comparisons between two detectors whose thresholds are approximately the same and thus enabled us to calculate the integral gradient for protons and alpha particles of $E \geqslant 50$ MeV/nucleon.

C. Orbit of Mariner 4

Mariner 4 was launched on a Mars-bound trajectory on 28 November 1964 and data transmission from the spacecraft was terminated on 1 October 1965. The trajectory of the spacecraft in a coordinate system where the earth-sun line is fixed is shown in Fig. 1. The spacecraft moved from ~ 1 A.U. to 1.57 A.U. in heliocentric radial distance, and the difference in heliocentric longitude between it and the earth toward the end of the mission reached ~ 100 degrees. Data were received from the spacecraft more or less continuously except for the periods 15 July to 3 August and 31 August to 2 September 1965. The University of Iowa detector package operated in the expected manner during the entire 10 months of observation.

IV. RESULTS

A. Effect of Forbush Decrease

Figure 2 shows a cross plot of 5-day-averaged counting rates from the IMP-OGO monitor versus similarly derived rates from detector C of Mariner 4 during the 10-month period of observations. Several points are labeled by the days of the year on which the observation was made so that one may easily follow the direction of the curve. We observe the following:

(1) The counting rate of detector C has a lower value at the end of the mission (days 270 to 274) than at the beginning. Note that the opposite is true for the IMP-OGO monitor. The regression line shows what the Mariner 4 detector would have counted if the spacecraft had remained in the vicinity of the earth.

(2) Following major Forbush decreases the slope of the curve is changed discontinuously and a new level of activity is established. Further, it is possible that Forbush decreases exhibit a different behavior at the positions of the two spacecrafts.

(3) Figure 2 suggests that the data can be naturally separated into four different periods, namely: days 334, 1964 to

14, 1965; 68 to 136; 137 to 193; and 222 to 273, 1965. The first and second periods are separated by a major Forbush decrease. The second period lasts up to solar minimum, while period 3 follows a sharp onset in solar activity. The last group corresponds to a time of relatively small changes in intensity.

To investigate item (2) we show in Fig. 3 cross plots for several Forbush decreases, as the difference in longitude as well as the radial distance between the two spacecraft increases. We observe that for small differences in heliocentric longitude the points are clustered together, that is, the Forbush decrease exhibits the same behavior at both spacecraft. As the difference in longitude increases, however, we observe that the two detectors respond differently during the onset and recovery phases, indicating that there are delays both in the onset and recovery times and/or changes in the absolute level of activity observed before and after a Forbush decrease at the two spacecrafts. Such behavior is not unexpected, if one considers that the gyroradius of a BeV proton in a 5 gamma field is $\sim 7 \times 10^{-3}$ A.U. and that, in the case in point, the two spacecrafts are separated by ~ 0.5 A.U. Thus with a longitude difference of $\sim 25°$ we observe that the Forbush decrease may be confined to a region smaller than 0.5×0.7 A.U. Note that this represents ~ 130 gyroradii for 1 BeV protons, so that the region is quite large as far as typical cosmic ray particles are concerned.

We conclude from the above analysis that, in attempting to measure the gradient of interplanetary particles, we should exclude data taken during Forbush decreases observed at either spacecraft.

B. Correlation Coefficients

To demonstrate that the IMP-OGO monitor and detector C (with its counting rate corrected in the manner discussed earlier) are indeed responding to the same radiation, we have plotted in Fig. 4 cross plots for four different periods, as indicated in Section IV-A.

Group 1

Group 1 shows data for the period beginning on day 334, 1964 to 14, 1965. During this period both spacecraft were within 0.07 A.U. of each other and the difference in their positions in heliocentric longitude was small (see Fig. 1). Thus we suggest that both spacecraft are measuring essentially the same particle flux in space and time. Analysis of the data shows that during this period, the correlation coefficient for the five-day averages is 0.904, and a least-square fit gives that

$$C_M = 1.336 \times 10^{-3} C_E + 0.02397 , \qquad (3)$$

where

C_M = counting rate of detector C in counts/second

C_E = counting rate at earth of IMP-OGO monitor in counts/hour.

The presence of the second term in Eq. (3) suggests that the two detectors do not have exactly identical energy thresholds and that as much as ~ 3% of the counting rate of detector C is due to particles not counted by the IMP-OGO monitor. We shall come back to this point in a later section. Meanwhile, we shall assume that Eq. (3) holds true during the entire mission, and will use it to predict what the counting rate of the Mariner instrument would have been, if it had remained in the vicinity of the earth.

Group 2

The second inset in Fig. 4 shows a regression plot for days 68 to 136, 1965, that is, up to the time of solar minimum as indicated by the IMP-OGO monitor, detector C, and the Deep River neutron monitor (see Fig. 5). The gap in the data between days 14 to 68 is due to the presence of several Forbush decreases as well as the unavailability of the IMP-OGO monitor data during this period. The solid line in the figure represents the regression line for days 334 to 14. We observe that during this period the counting rate of detector C is generally below that predicted by the IMP-OGO monitor, in the absence of time variations. Further, the correlation coefficient during this period ~ 0.45, although a general increase in the IMP-OGO monitor is accompanied by a general but not pronounced increase in detector C.

Group 3

This group shows data for days 137 to 193, 1965. During this period a precipitous decrease in the cosmic ray intensity took place, as shown in Fig. 5. Inspection of the third inset in Fig. 4 shows that the correspondence between the IMP-OGO monitor and detector C counting rates is comparable to that in Group 1. Detailed analysis during this period shows that the correlation coefficient for the five-day averages is 0.93 and a least-square fit to the data gives

$$C_M = 1.31 \times 10^{-3} C_E - 0.0058 \ . \qquad (4)$$

We observe that the slope is essentially identical (within 1%) to the one computed for days 334 to 14 but that the intercept is different, although it represents a smaller percentage (~ 1%) of the counting rate of C than in the case of Eq. (3).

This fact suggests that detector C and the IMP-OGO monitor have the same effective energy threshold to incident particles during this period. We have included the regression line given by Eq. (4) in all four periods for comparison (dashed line).

Group 4

The data from all detectors during this period (222 to 273) show relatively little change (see Fig. 5). We again observe in Fig. 4 that detector C has a lower counting rate than what Eqs. (3) or (4) would predict if there were no time variations. The correlation coefficient for the five-day averages is 0.61.

C. Counting Rates vs Time

Figure 5 shows five-day averages of the actual counting rates of detector C and the IMP-OGO monitor as well as the smoothed Deep River neutron monitor, and the smoothed sunspot cycle number as a function of time. The radial separation between the earth and Mariner 4 has been included for comparison. The heavy lines on the counting rates of the two detectors indicate periods during which Forbush decreases have taken place so that the data were excluded in the evaluation of the gradients. It is apparent from this plot that, at times, there is one-to-one correspondence between changes in the intensity of the IMP-OGO monitor and detector C on Mariner 4. One also sees that our earlier division of data into four logical groups is justified. In fact, the detailed correspondence between the monitor detector and detector C for days 334 to 14 is evident, hence the choice of this period as the interval for establishing the relationship between the two detectors, as shown by Eq. (3).

There appears to be little correlation between the reference detector and C for days 68 to 138, although all the Forbush decreases observed by detector C were also seen by the neutron monitor. Note that in one instance (days 108 to 115) the IMP-OGO monitor does not agree with either the neutron monitor or detector C; this is probably due to the presence of protons $E_p \geqslant 50$ MeV in the plasma stream that produced the 17 April 1965 magnetic storm [Burns and Krimigis, 1969]. It is worthwhile to observe that the smoothed sunspot number was generally low during this entire period, which helps to explain the low correlation coefficient between the IMP-OGO monitor and detector C.

There is a general decrease in the counting rates of detector C, the IMP-OGO monitor, and the neutron monitor, coincident with the apparent onset of the new solar activity cycle, as indicated by the increase in the production of low energy solar particles [Krimigis and Van Allen, 1966] and the increase in sunspot number. It appears that during this period (days 137 to 193) the region encompassing the earth and Mariner 4 came under the influence of a single modulating medium. As noted earlier in connection with Eq. (4), it appears that both detector C and the IMP-OGO monitor are responding to the same incident radiation.

Finally we note from Fig. 5 that during the last period (days 222 to 273) the level of intensity remained relatively constant for all detectors, although this level is lower than the initial one for the Mariner detector, while the inverse is true for the reference detector. We shall come back to this point at a later time.

To facilitate a direct comparison of the increases and decreases of the counting rates we have replotted in Fig. 6 the data shown in the previous figure on a percentage basis. We have chosen the average counting rate for days 334 to 14 as 100 percent. The periods during which Forbush decreases took place are again emphasized with a heavy line. If we now take the interval between days 20 and 136 we observe the following:

(1) The increase of the IMP-OGO monitor is $\sim 9\%$.

(2) The line of maximum positive slope consistent with the Mariner 4 data shows that the increase of detector C is $\sim 4\%$.

(3) Thus, assuming that both detectors have approximately the same energy threshold ($E \geqslant 50$ MeV/nucleon) we conclude that the gradient must have the value $(4-9)\%/0.3$ A.U. or -16.6% per A.U.

Using similar arguments for days 137 to 193, we conclude that the gradient must have the value -12% per A.U.

Note that the values of the gradient derived in this manner are valid provided that the counting efficiency of each detector did not change during either of the two periods of observation. The similarity of the two results indicate that this was indeed the case.

D. Ratio vs ΔR

To place the above results on a more quantitative basis and utilize all the data, we assume that the counting rate of the Mariner 4 detector consists of the sum of what the detector would be reading in the vicinity of the earth (C_{ME}) plus a contribution from the presumed gradient of cosmic radiation (C_G), i.e.,

$$C_M = C_{ME} + C_G \ . \tag{5}$$

We assume that

$$C_{ME} = aC_E + b \ , \tag{6}$$

where a and b are constants as shown by Eqs. (3) and (4) and that, to first order in ΔR, we have

$$C_G = C_{ME}\, G\Delta R \ , \tag{7}$$

where G represents the gradient. Thus we obtain

$$C_M = (aC_E + b)(1 + G\Delta R) \ , \tag{8}$$

where the first factor is given by Eqs. (3) and/or (4) and the value of G is to be evaluated from the data.

By rearranging terms in Eq. (8), we have that

$$\frac{C_M}{aC_E + b} = 1 + G\Delta R \ , \tag{9}$$

where the ratio $\frac{C_M}{aC_E + b}$ is equal to the ratio of the respective flux of particles at Mariner and at earth, that is:

$$\frac{C_M}{aC_E + b} = \frac{\Phi_M}{\Phi_E} \tag{10}$$

and finally

$$\frac{\Phi_M}{\Phi_E} = 1 + G\Delta R \ . \tag{11}$$

This ratio has been plotted versus ΔR in Fig. 7, with the values of Φ_E predicted by using Eq. (3) (top inset) and Eq. (4) (bottom inset). The break in the data around -0.2 A.U. is due to the lack of data from the IMP-OGO monitor during this period. A least square fit to the data gives the following values for G:

$G = -14.5\%/A.U.$ — normalization to days 334 to 14

$G = 15.7\%/A.U.$ — normalization to days 137 to 193 .

The mean value for the two normalizations is

$$G = -15.1\%/A.U. \tag{12}$$

with a probable error of $\pm$ 1%/A.U.

The result shown in Eq. (12) confirms the approximate values estimated in Section IV-C for the separate periods on days 20 to 136 and 137 to 193 and precludes any possibility that this may be a fortuitous result. We note that during the last period (days 222 to 273) the data could be fitted by a straight line. This is in agreement with the fact that the change in radial distance between the two spacecraft remains approximately constant.

V. DISCUSSION

A. Comparison with Other Observations

The results presented in the previous section may be compared with similar data obtained on the same spacecraft by O'Gallagher and Simpson [1967], O'Gallagher [1967], Krimigis [1968], and Anderson [1968] and with data obtained on the Soviet spacecrafts Zond 3 and Venus 2 [Vernov et al., 1966; 1967]. Table I summarizes these results. It is obvious that the results of O'Gallagher, Anderson, and of the present work are in direct conflict. Further, results of Anderson [1968], Krimigis [1968], and of the present work are irreconcilable with those of O'Gallagher [1967]. We shall not attempt here a detailed discussion of O'Gallagher's results; we refer the reader to the original paper, where the corrections to the data that were necessary in order to obtain the quoted values are described in detail. We do note that a plot of his (O'Gallagher's) data, from which the integral gradient was derived, versus the University of Minnesota OGO-I ion chamber shows a good correlation between the two sets of data during periods of increasing as well as decreasing cosmic ray intensity without any hysteresis effect. However, when the two instruments are plotted individually against a neutron monitor, a hysteresis effect of nearly equal magnitude can be clearly seen in both cases. This indicates that the

TABLE I: Measured Radial Gradients during Solar Minimum

Spacecraft	Year	Particle Type	Kinetic Energy	Gradient %/A.U.	Radial Range	References
Mariner 4	1965	Protons	20-30 MeV	500 ± 135	1-1.57	O'Gallagher and Simpson [1967] and O'Gallagher [1967]
			30-60 MeV	187 ± 63		
			70-100 MeV	145 ± 63		
			Mean 5 BeV	9 ± 1		
		Alphas	100-300 MeV/nuc	75 ± 13	1-1.57	
			300-420 MeV/nuc	55 ± 11		
		Protons	> 430 MeV	< 3	1-1.57	Krimigis [1968]
		Ionization	> 10 MeV/nuc	6.8 ± 1.6	1.12-1.28	Anderson [1968]
		Protons & Alphas	> 50 MeV/nuc	-15.1 ± 1	1.-1.57	Present Work
Zond 3 and Venus 2	1965-1966	Protons & Alphas	> 30 MeV/nuc	1 ± 0.1*	0.9-1.28	Vernov et al. [1967]

*See text

intensity variation observed by O'Gallagher and attributed to the gradient could be mostly due to the time variation of cosmic ray intensity during the Mariner 4 mission [Kane and Winckler, private communication, 1968]. Further, his result has been questioned by Balasubrahmanyan et al. [1968] from modulation and spectrum observations during solar minimum.

Regarding Anderson's [1968] result, we note the following:

(1) His data cover a range ~ 0.28 A.U. only or up to day 78, 1965, at which time the ion chamber ceased operation.

(2) As Anderson [1967] remarks and as is apparent from his Fig. 8, Anderson [1968], no gradient effect was observed in his data until after the 5 February 1965 solar particle event, at which time his GM tube failed. In fact, the correlation coefficient between the daily-averaged counting rates of his ion chamber (kindly made available to us by Dr. Anderson) and detector C was ~ 0.73 for days 334 to 14, but was only ~ 0.2 for days 14 to 78 during the period that his gradient effect was observed. This comparison suggests that his determination of the gradient may have been an instrumental effect.

(3) During the period that his gradient effect was observed, several Forbush decreases took place, which as we have shown here, should not be included in the calculation of the gradient.

(4) Anderson [1965] has shown that the gradient in flux and ionization are not necessarily the same. His results from Mariner 2 show that although the ionization gradient was ~ 9%/A.U., the flux gradient was 0 ± 15%/A.U.

In view of the above, we consider that Anderson's result is not indicative of the true interplanetary gradient during solar minimum.

In regard to the results obtained with data from Zond 3 and Venus 2 [Vernov et al., 1966; 1967] we note that the values obtained range from 3.4%/A.U. (1966) to 1%/A.U. (1967). Further, the gradient for both of these values was derived by taking two periods, 15 to 21 November 1965 and 4 to 11 January 1966, and comparing the average counting rates during these periods. During the second period, however, recovery from a Forbush decrease was in progress, and as we have shown, such data should not be included in the computation of the gradient. In view of these facts we do not consider the results of Vernov et al. as representative of the gradient during solar minimum.

B. Consideration of Spurious Effects

We should consider the possibility that the present result is perhaps an instrumental effect. It is possible, for example, that the counting efficiency of the GM tube declined gradually in such a way that it more than compensated for any increase due to a positive gradient. This decline in efficiency could come about in two ways: (a) a decrease in the efficiency as the temperature of the detector decreased and (b) a change in the operating voltage of the GM tube.

In regard to (a) above we note that preflight temperature calibrations show that over the temperature range of interest (28°C on day 334, 1964 to 9°C on day 273, 1965), the efficiency of the detector changes by less than 1%. Further, the background counting rate of the two additional thin-window GM tubes described in Section II behaved exactly as predicted from their preflight calibration curves. Specifically [Krimigis, 1968], the background rate of detector A decreased by approximately 15%, while that of B remained constant, in agreement with the preflight calibrations. We thus conclude that the observed effect cannot be explained as a change in counting efficiency of the detector due to temperature variations.

A change in the operating voltage of the GM tube as noted in (b) above, although possible, is highly unlikely in this case. Preflight data show that the change in the voltage of the VR (Voltage Regulator) tube was less than 1% in the temperature range -50°C to +75°C. Further, plateau curves of the GM tube taken with a standard source show that the curves are identical over a period of $\sim$ 4 months, with a slope in the region of interest of $\sim$ 0.06% per volt. In addition, the instrument showed no apparent change in efficiency in $\sim$ 8 months of testing prior to launch.

An inflight check of the efficiency may be made by comparing the regression relations obtained between the IMP-OGO monitor and detector C during the two periods (days 334 to 14 and 137 to 193) for which the correlation coefficient is ~ 0.9 between the two detectors. We observe from Eqs. (3) and (4) that the respective slopes are 1.336×10^{-3} and 1.316×10^{-3}. The difference between the two slopes is $\sim 1.5\%$, indicating that the efficiency of either counter could not have changed significantly over a period of ~ 8 months.

We conclude from the discussion in this section that the observed result cannot be accounted for by consideration of spurious effects associated with the operation of the instrument.

VI. FURTHER EXPERIMENTAL DATA

Following the termination of data reception from the Mariner 4 spacecraft, efforts were made to reacquire the spacecraft using the Jet Propulsion Laboratory's Goldstone 210-foot dish. Sporadic data were received from the spacecraft beginning ~ May 1966, while during late spring and early summer of 1967 Mariner 4 was close enough to the earth so that data of good quality were obtained using the facilities of the Deep Space Network, although on low-priority-low duty-cycle basis.

The University of Iowa detector package operated in the expected manner during the reacquisition period, and data from detector C are plotted in Fig. 8, together with the data obtained during the 1964-1965 period. We observe that the counting rate of C during 1967 is approximately 65 to 70 percent of the late 1964—early 1965 level. Unfortunately the IMP-OGO monitor failed in early May 1967 so that a detailed comparison of the counting rates between it and detector C is not possible. We can, however, make an approximate comparison by noting that the late April—early May 1967 counting rate of the IMP-OGO detector was ~ 3900 counts/hour or ~ 87% of the 1964-1965 normalization period (days 334 to 14). Using Eq. (3) we can predict what the Mariner 4 counting rate should have been during this period and we find that

$$C_M = 0.55 \text{ counts/second}$$

if Mariner 4 had stayed in the vicinity of the earth. In terms of the 1964-1965 normalization period, 0.55 counts/second corresponds to 83 percent. Now, the observed rate of detector C during May 1967 may be taken as ~ 70 percent. Thus we have that the observed and calculated rates differ by -13%. Noting that the differences in heliocentric radial distance between the earth and Mariner 4 is ~ 0.55 A.U. (Fig. 8), we conclude that the gradient during May 1967 has the value

$$G = \frac{-13\%}{0.55 \text{ A.U.}} = (-24 \pm 4)\%/\text{A.U.}$$

Hence, the 1967 observations confirm our 1965 result and show that the magnitude of the gradient increases as solar activity increases.

Further, we can check this result by comparing the Mariner 4 data with those obtained from Mariner 5, which was launched in a Venus-bound trajectory on 14 June 1967. The detector complement on Mariner 5 includes a GM tube identical in all respects to detector C of Mariner 4, although preflight calibrations comparing the absolute efficiencies of the two detectors are not available. The result of this comparison is shown in Fig. 9.

The Mariner 5 data have been corrected in a manner similar to the one outlined earlier for the Mariner 4 data. The fluctuations of the Mariner data is due to the relatively poor statistics. Taken as a whole, however, we observe that the Mariner 5 counting rate is consistently higher than that of Mariner 4 and the ratio of the rates is roughly constant; the difference in heliocentric radial distance between the two spacecraft is roughly constant throughout the whole period at ~ 0.475 A.U. Thus we have a measurement of the gradient for days 200 to 300, 1967, given by

$$G \simeq \frac{-13.7\%}{0.475 \text{ A.U.}} = (-29 \pm 4)\%/\text{A.U.}$$

This measurement is independent of any assumption regarding the instruments, since the properties of the two detectors are similar and the absolute efficiencies are expected to be the same. Further, the result is in good agreement with the value obtained earlier by comparing the IMP-OGO monitor and Mariner 4 in May of 1967. The internal consistency between the three sets of data lends further support to the result of the analysis performed on the much larger body of 1965 data by comparing the IMP-OGO monitor and the Mariner 4 detector.

VII. PHYSICAL SIGNIFICANCE OF THE RESULTS

As noted in the introduction, one expects a positive gradient or, during solar minimum, possibly a zero gradient. Thus, the result of this study implies a source of $E \geqslant 50$ MeV/nucleon inside the orbit of earth. If we assume that all of the measured flux comes from the sun, and that it propagates radially outward in three dimensions, then we have that

$$\Phi = \frac{K}{r^2}$$

$$\frac{d\Phi}{dr} = -\frac{2K}{r^3}$$

$$\frac{d\Phi}{\Phi} = -\frac{2}{r}\,dr \qquad (13)$$

and

$$\frac{\frac{d\Phi}{\Phi}}{dr} = -\frac{2}{r}\,. \qquad (14)$$

Assuming r to be the mean of 1.0 and 1.57 A.U., we have that

$$\frac{\frac{d\Phi}{\Phi}}{dr} \simeq -\frac{2}{1.285\ \text{A.U.}} = -1.55\,.$$

That is, if the source of all observed particles was the sun, then one would observe a gradient of -155% per A.U. Clearly, this is not observed, so we assume that the flux observed by detector C and the IMP-OGO monitor must consist of both solar and galactic cosmic ray particles, that is

$$\Phi = \alpha\ \Phi_S + \beta\ \Phi_G \tag{15}$$

$$\frac{d\Phi}{dr} = \alpha \frac{d\Phi_S}{dr} + \beta \frac{d\Phi_G}{dr}\ , \tag{16}$$

where Φ is the total flux, α and β are constants, and Φ_S and Φ_G are the solar and galactic particle flux, respectively.

If we assume that

$$\frac{d\Phi_G}{dr} \geq 0$$

then

$$\frac{d\Phi}{dr} \leq \alpha \frac{d\Phi_S}{dr}$$

$$\alpha \geqslant \frac{\frac{d\Phi}{dr}}{\frac{d\Phi_S}{dr}} = \frac{-15.1}{-155} \simeq 0.1\ .$$

Thus we have obtained a lower limit for the fractional contribution of solar particles to the flux of interplanetary protons and alpha particles of $E \geqslant 50$ MeV/nucleon.

Independently of what the percentage of solar contribution is to the interplanetary particle flux of $E \geqslant 50$ MeV/nucleon, the fact remains that in this energy range and during solar minimum we have a gradient directed <u>towards</u> the sun rather than away from the sun, as had been assumed in the past.

Evidence for a negative gradient has been in existence for some time. For example, Meyer and Vogt [1963] observed that the cosmic ray energy spectrum showed a broad minimum around 200 MeV during 1961, with a positive exponent for energies > 200 MeV and a negative exponent at energies < 200 MeV. They suggested that those protons of energy < 200 MeV were of solar origin with long (> 1 year) storage times in the solar system and/or continuous replenishment. Further, satellite observations of the differential energy spectrum of interplanetary particles during solar minimum (summarized by Gloeckler and Jokipii [1967]) show that there exists a broad minimum in the range of 10 to 40 MeV/nucleon with the slope showing a tendency to become positive below ~ 30 MeV/nucleon. Similar observations of the spectrum of protons and alpha particles at low (~ 30 MeV/nucleon) energies during different parts of the solar cycle led Fan et al. [1968] to suggest that protons of solar origin were added steadily to the interplanetary particle population as solar activity increased. Thus, the form of the differential energy spectrum, even at the time of solar minimum, suggests that there is a finite contribution from solar particles up to and perhaps greater than 50 MeV/nucleon.

In addition to the evidence from the spectrum pointing to a negative gradient, Rao, McCracken, and Bartley [1967] in studying the cosmic ray propagation effect conclude that "the 10 MeV/nucleon cosmic radiation possessed a density gradient directed toward the sun" and further that, "the cosmic radiation density gradient reverses its direction somewhere in the range $10 < E < 1000$ MeV." It is noted that their observations were made during December to April 1965 and August through November 1966, i.e., during and close to solar minimum. The conclusions of Rao et al. [1967] have recently been challenged by Jokipii and Parker [1968]. They interpret the observed anisotropy of particles of $E \geqslant 10$ MeV/nucleon as due to the fact that the cosmic ray gradient is very much less between the sun and earth than the observed gradient of O'Gallagher [1967] between the earth and Mars. They also discuss the possibility that $K_{\perp} \simeq K_{\parallel}$ (where $K_{\perp}$ and $K_{\parallel}$ are the diffusion coefficient perpendicular and parallel to the lines of force of the interplanetary magnetic field, respectively) due to large power at very small wave numbers in the spectrum of the interplanetary field.

Thus, our result establishes the interpretation of the anisotropy by Rao et al. [1967] as due to emission of solar particles. In fact, Jokipii and Parker [1968] have no fundamental objection to this interpretation. In addition, the assumption $K_{\perp} \approx K_{\parallel}$ need not be considered further in this connection, since it is highly improbable on the basis of other observations [Jokipii, 1968; Lin et al., 1968].

We conclude that our result confirms previous deductions with respect to the gradient obtained from single spacecraft observations and gives an actual measurement of this gradient. It also points out that it is impossible to measure the true gradient of galactic cosmic rays at $E \sim 50$ MeV/nucleon, even at the time of solar minimum.

VIII. CONCLUSIONS

By use of simultaneous observations with similar detectors on IMP-OGO and Mariner 4, we have shown that:

(1) As the difference in heliocentric longitude between two spacecraft increases, there exist inhomogeneities in the time and/or space development of a Forbush decrease. It is estimated that the Forbush decrease region may be as small as 0.5 x 0.7 A.U.

(2) By comparing counting rates of the two spacecraft during quiet times we show that the gradient in the intensity of protons and alpha particles in interplanetary space at $E \geqslant 50$ MeV/nucleon is directed towards the sun and has a magnitude of 15.1%/A.U. during the solar minimum period of 1964-1965.

(3) Using data from Mariner 4, Mariner 5, and IMP-OGO, we show that the value of the gradient during the period May to November 1967 ranged from -24 to -29%/A.U. Hence, the magnitude of the gradient increases with solar activity.

(4) It is shown that the interplanetary flux of protons and helium nuclei of $E \geqslant 50$ MeV/nucleon must consist of particles of solar as well as galactic origin. The solar contribution must be > 10 percent.

(5) In view of the above results, we argue that it is impossible to measure the gradient of galactic cosmic radiation of $E \sim 50$ MeV/nucleon even at the time of solar minimum.

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FIGURE CAPTIONS

Figure 1. The orbit of Mariner 4 in the ecliptic plane in a coordinate system where the earth-sun line is fixed. Note that toward the end of the mission (day 274) the difference in heliocentric longitude between the earth and the spacecraft is $\sim 100°$.

Figure 2. A cross-plot of detector C and the earth-orbiting IMP-OGO monitor. The dashed line shows a least-square fit to the data for days 334, 1964, to 14, 1965. The arrow indicates the sense of the curve as a function of time, and the numbers the day of year when the observation was made.

Figure 3. A cross-plot of daily averaged rates from detector C and the IMP-OGO monitor. Note that as the difference in heliocentric longitude between the two spacecraft increases, the onset and recovery phases of the Forbush decrease appear markedly different.

Figure 4. Scatter plot of 1-day and 5-day averages from detector C and the IMP-OGO monitor. The lines resulting from least-square fits for days 334, 1964 to 14, 1965 and 137 to 193, 1965 are shown in all four insets. The correlation coefficients for the four successive periods are 0.90, 0.45, 0.93, and 0.61, respectively.

Figure 5. The 5-day averaged counting rates from detector C and the IMP-OGO monitor. The smoothed neutron monitor and sunspot number curves are shown for comparison. Note that the Forbush decrease around day 110 was not seen by the IMP-OGO monitor, although registered by both detector C and the neutron monitor.

Figure 6. The same as Figure 5, but on a percent basis. Here, the actual 5-day averaged rates of the neutron monitor are shown.

Figure 7. The ratio of fluxes at Mariner and earth are plotted as a function of the difference in heliocentric radial distance. The lack of points around $\Delta R \sim 0.2$ is due to unavailability of IMP-OGO data. The value of the gradient obtained from a least-square fit of the data is shown.

Figure 8. All the data obtained from Mariner 4 in the period 1964 to 1967 are shown as a percent of the 1964-1965 (days 334 to 14) level. The neutron monitor and solar sunspot number curves are shown for comparison. The rate of detector C during May of 1967 predicted from the IMP-OGO monitor is $\sim$ 83 percent (see text).

Figure 9. The 5-day-averaged counting rates from similar detectors on Mariner 4 and Mariner 5 during part of 1967. Note that the ratio of the two counting rates does not appear to change, in concordance with the small change in ΔR.

G68-956

MARINER IV ORBIT IN SYSTEM WHERE EARTH-SUN LINE IS FIXED.

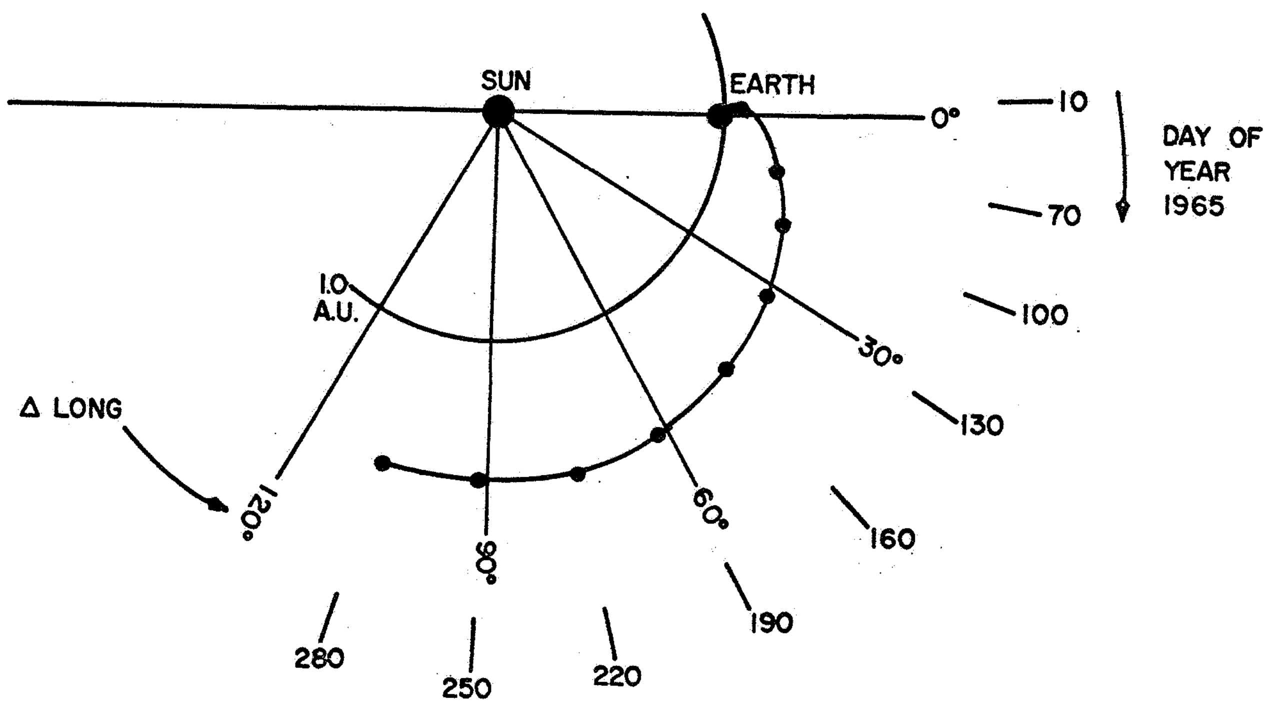
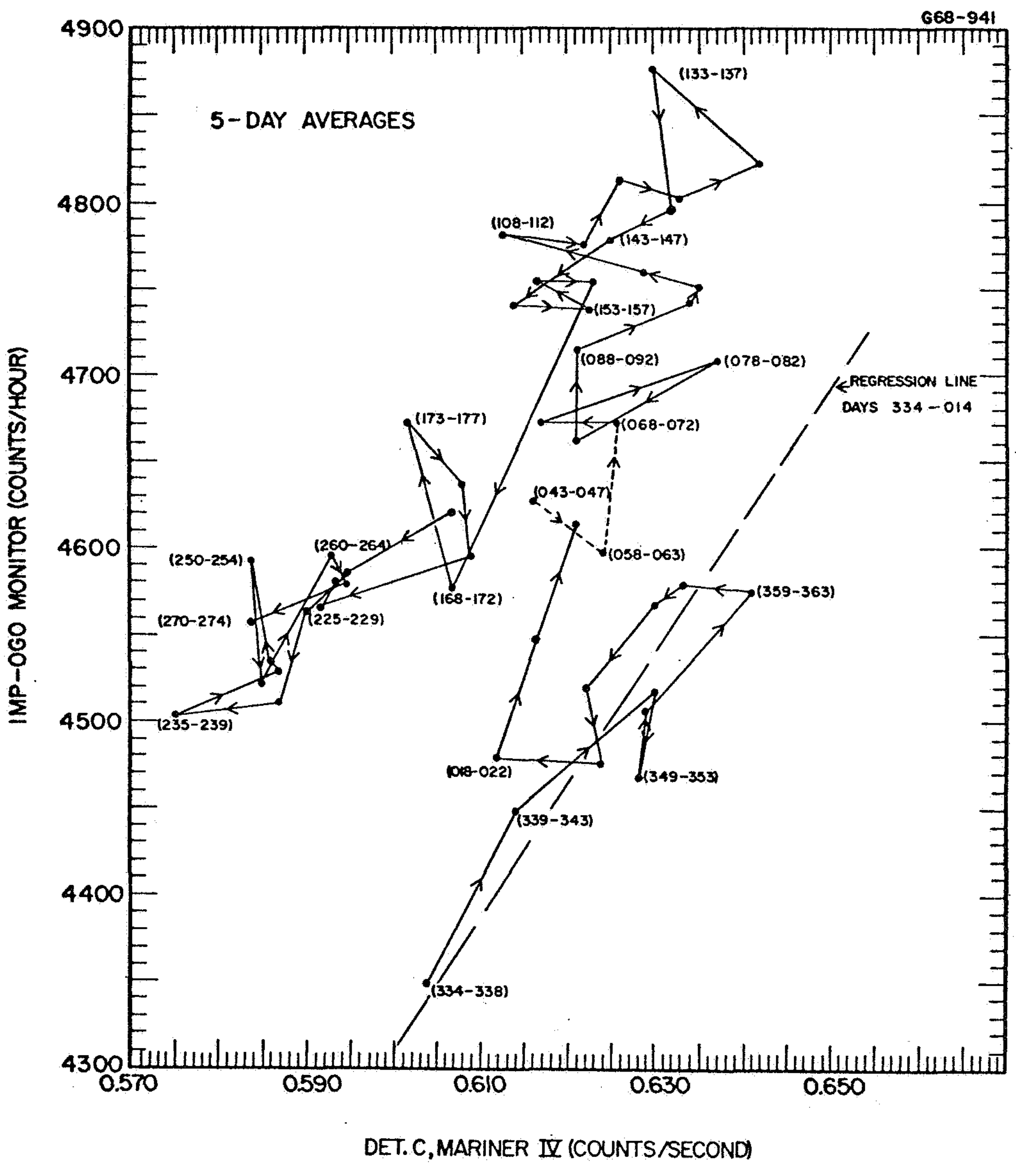


Figure 1



G68-941
5-DAY AVERAGES
IMP-OGO MONITOR (COUNTS/HOUR)
DET. C, MARINER IV (COUNTS/SECOND)
4900
4800
4700
4600
4500
4400
4300
0.570
0.590
0.610
0.630
0.650
(133-137)
(108-112)
(143-147)
(153-157)
(088-092)
(078-082)
REGRESSION LINE
DAYS 334 - 014
(173-177)
(068-072)
(043-047)
(058-063)
(260-264)
(250-254)
(168-172)
(270-274)
(225-229)
(359-363)
(235-239)
(018-022)
(349-353)
(339-343)
(334-338)

Figure 2

G68-954

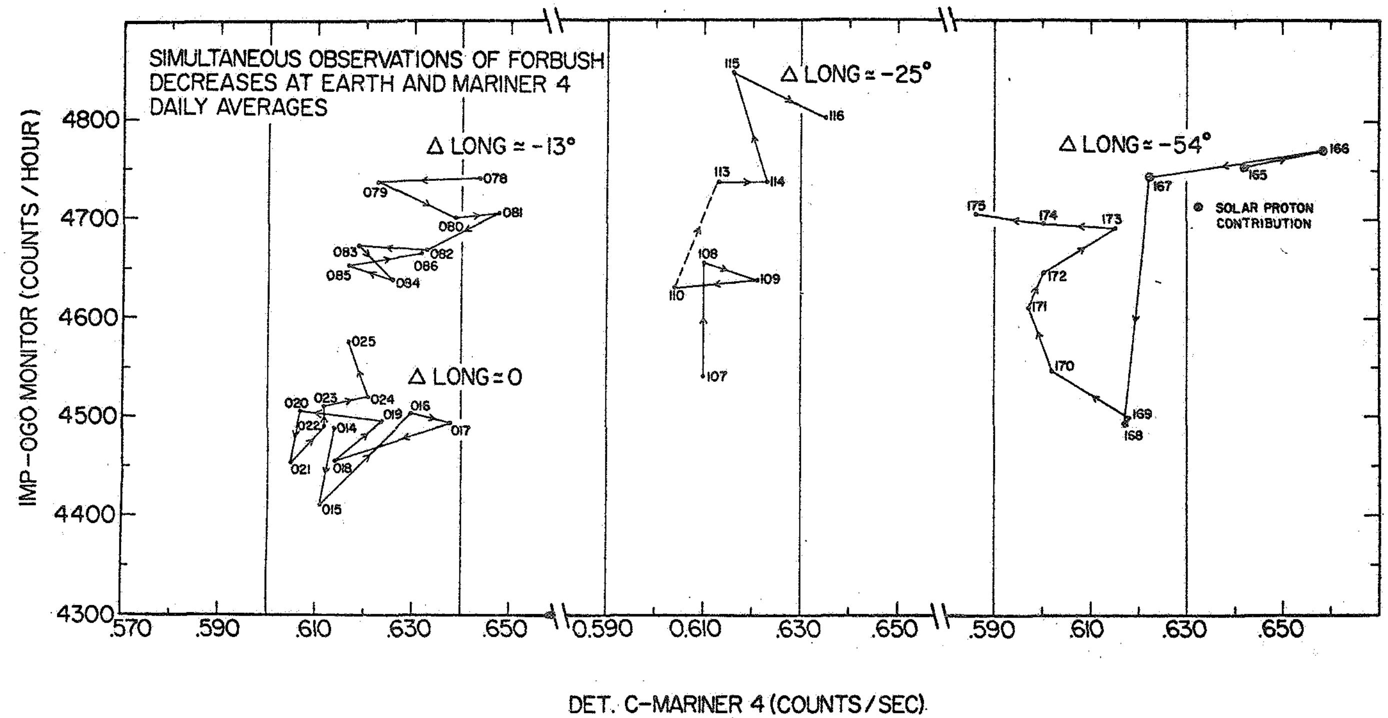


Figure 3

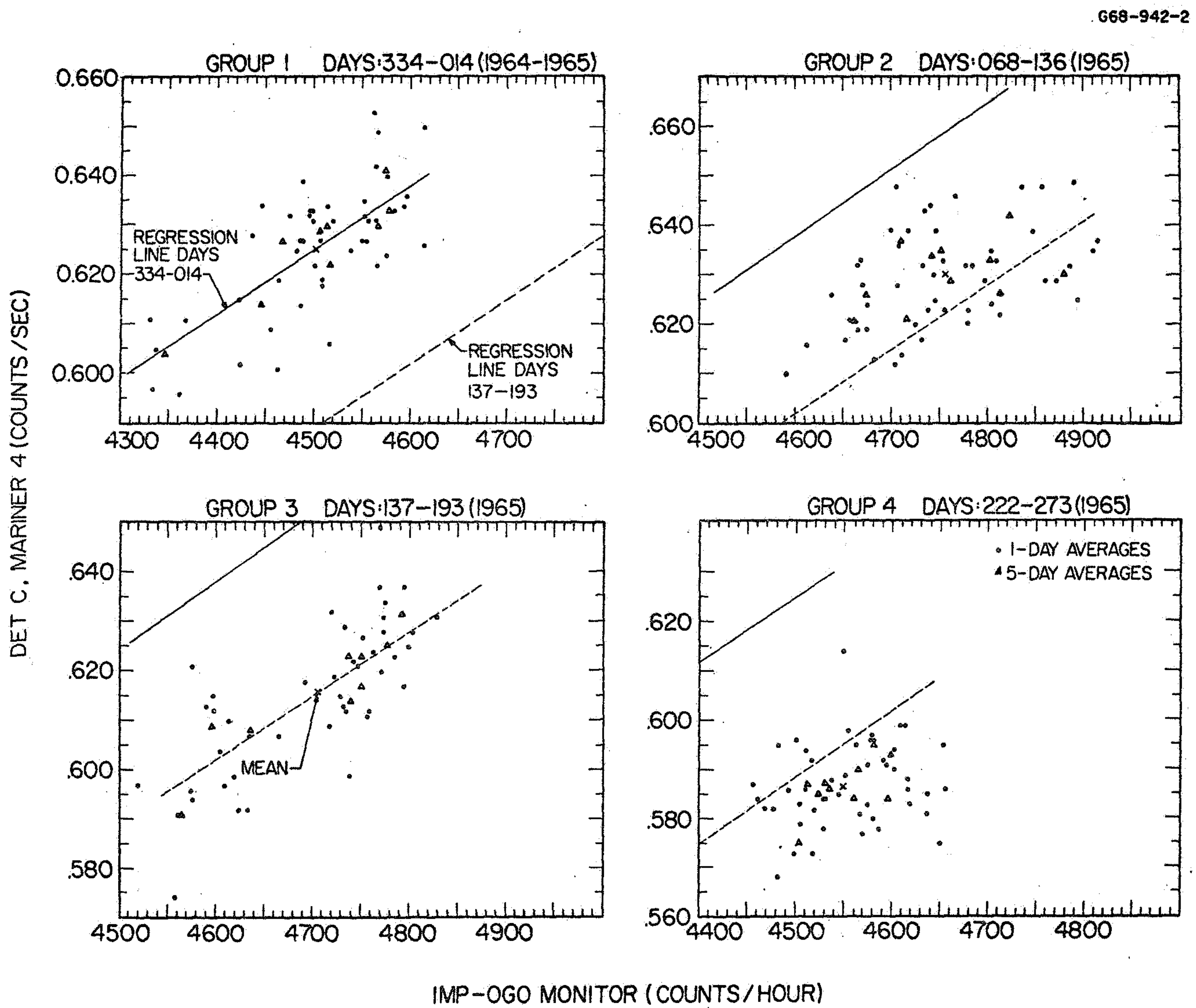

G68-942-2
GROUP 1 DAYS:334-014 (1964-1965)
REGRESSION
LINE DAYS
334-014
REGRESSION
LINE DAYS
137-193
GROUP 2 DAYS:068-136 (1965)
GROUP 3 DAYS:137-193 (1965)
MEAN
GROUP 4 DAYS:222-273 (1965)
1-DAY AVERAGES
5-DAY AVERAGES
DET C, MARINER 4 (COUNTS/SEC)
IMP-OGO MONITOR (COUNTS/HOUR)

Figure 4

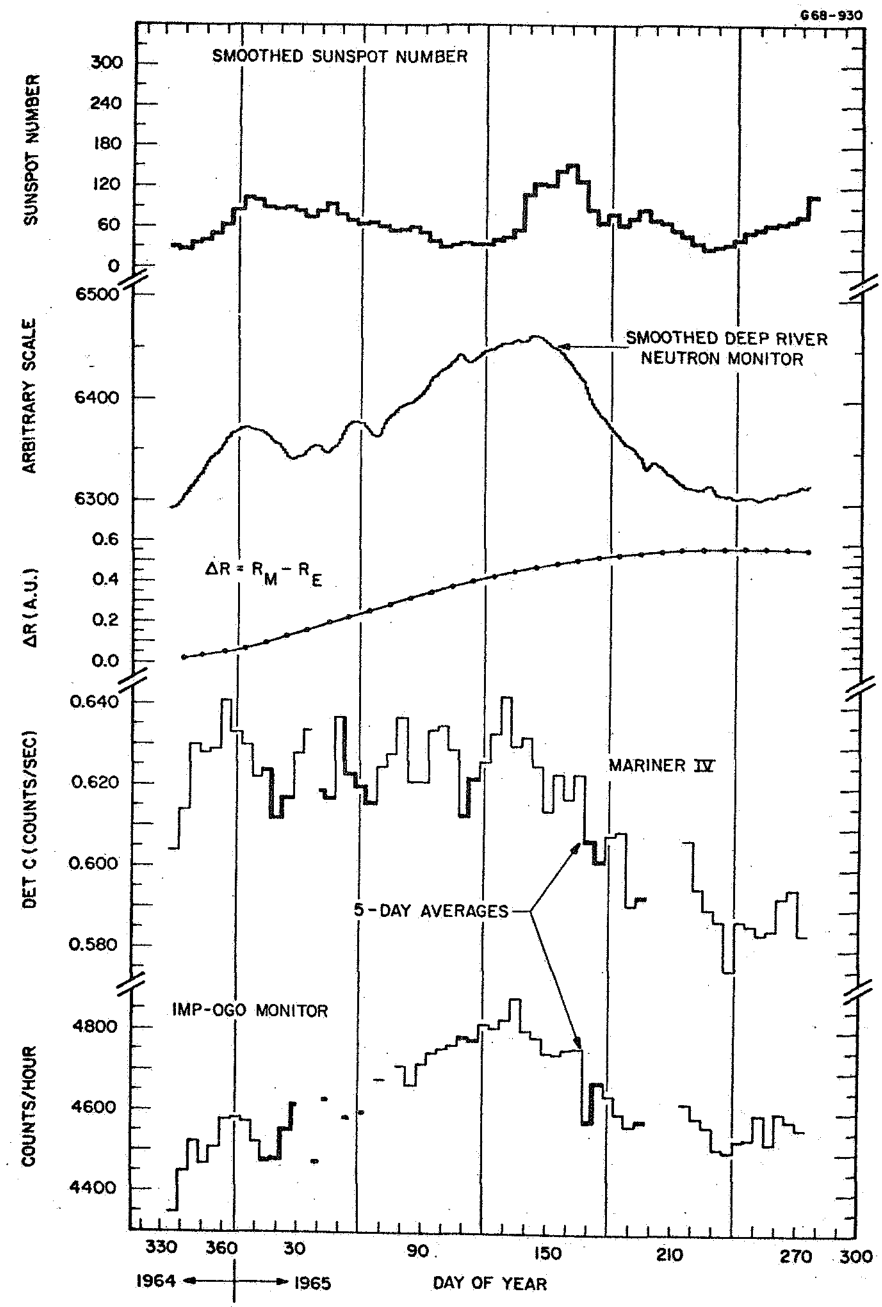

G68-930
SMOOTHED SUNSPOT NUMBER
SUNSPOT NUMBER
300
240
180
120
60
0
6500
ARBITRARY SCALE
6400
6300
SMOOTHED DEEP RIVER NEUTRON MONITOR
0.6
0.4
0.2
0.0
ΔR (A.U.)
$\Delta R = R_M - R_E$
0.640
0.620
0.600
0.580
DET C (COUNTS/SEC)
MARINER IV
5-DAY AVERAGES
IMP-OGO MONITOR
4800
4600
4400
COUNTS/HOUR
330
360
30
90
150
210
270
300
1964
1965
DAY OF YEAR

Figure 5

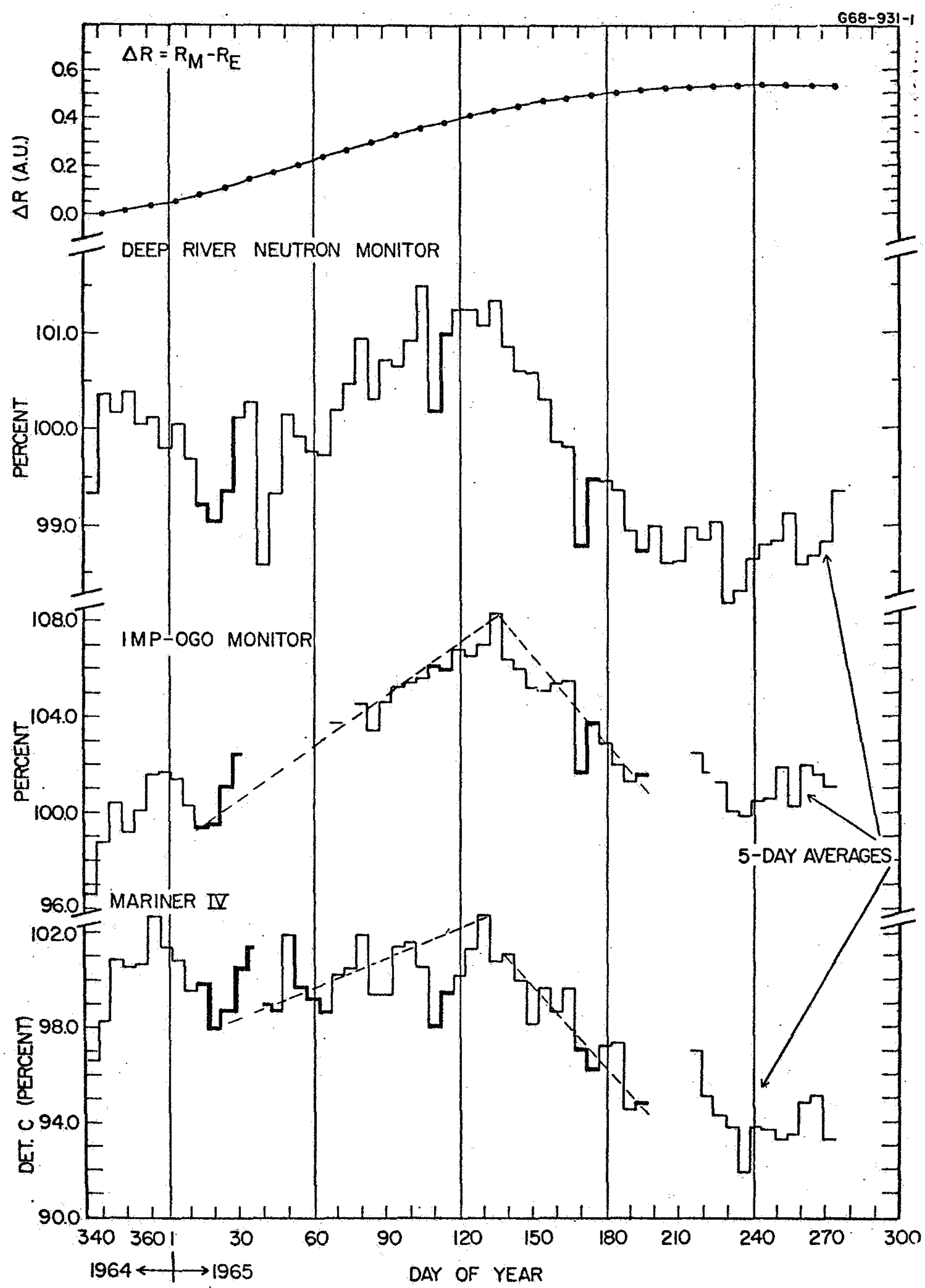
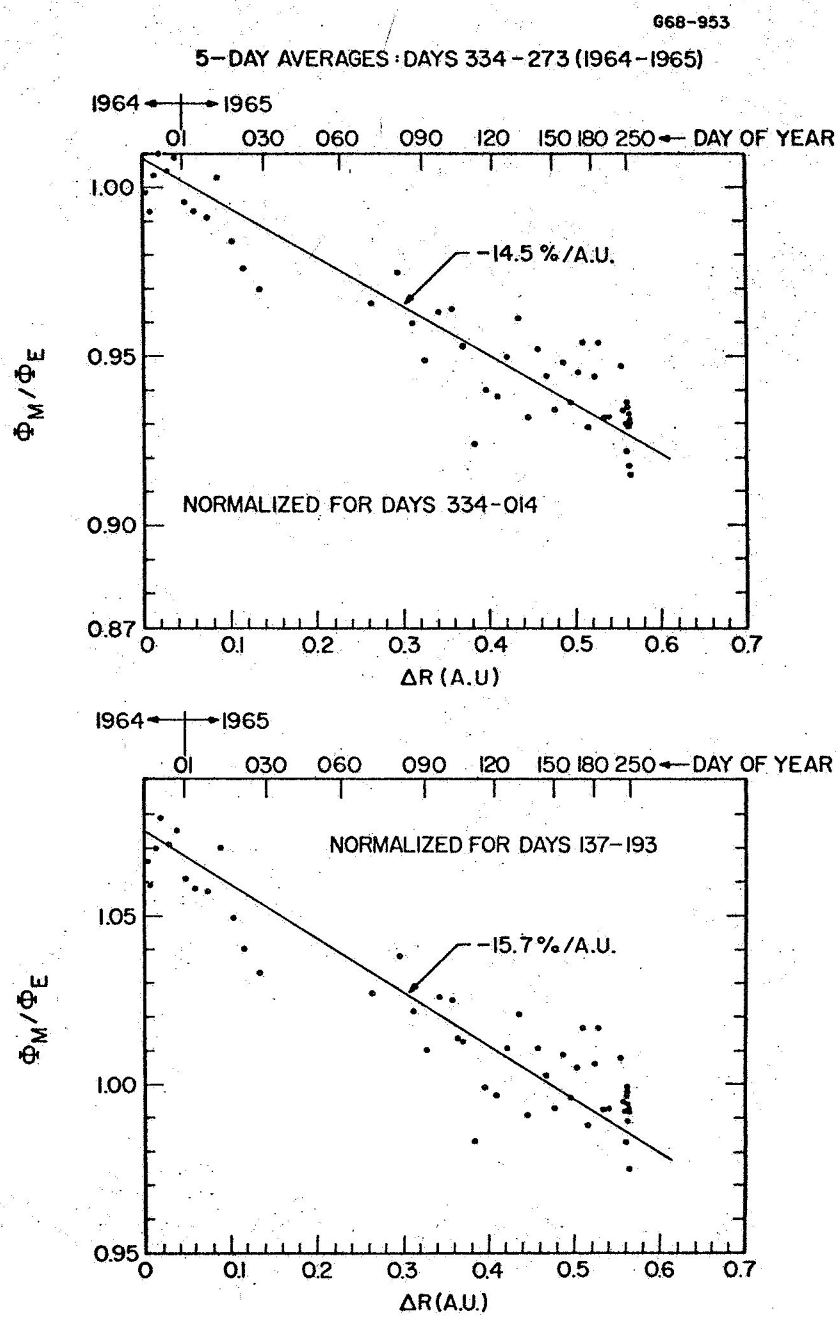
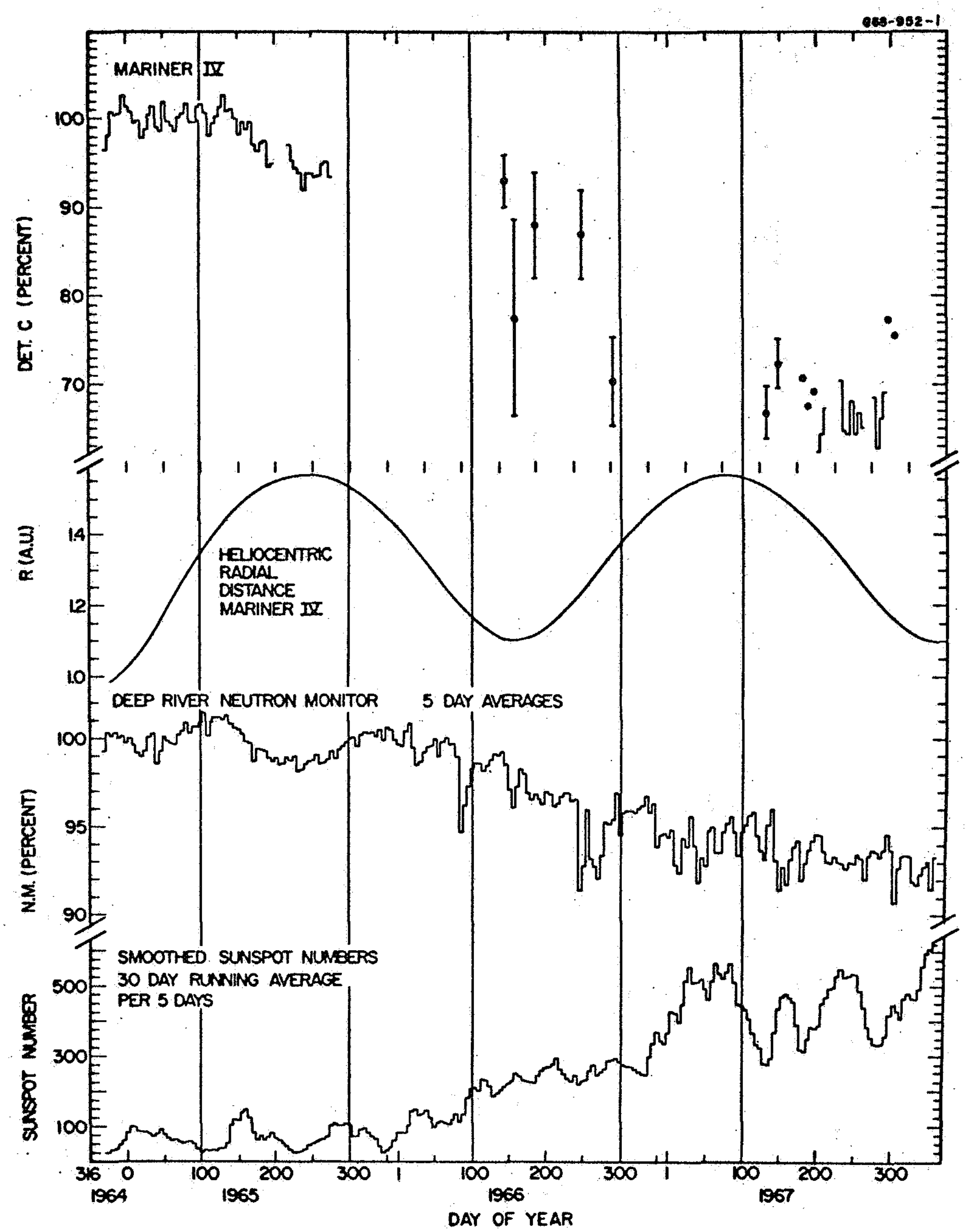

G68-931-1
ΔR = R_M - R_E
ΔR (A.U.)
0.6
0.4
0.2
0.0
DEEP RIVER NEUTRON MONITOR
PERCENT
101.0
100.0
99.0
108.0
IMP-OGO MONITOR
PERCENT
104.0
100.0
96.0
MARINER IV
102.0
DET. C (PERCENT)
98.0
94.0
90.0
5-DAY AVERAGES
340 360 1 30 60 90 120 150 180 210 240 270 300
1964 1965
DAY OF YEAR

Figure 6



G68-953
5-DAY AVERAGES: DAYS 334-273 (1964-1965)
1964 1965
01 030 060 090 120 150 180 250 DAY OF YEAR
1.00
0.95
0.90
0.87
-14.5 %/A.U.
NORMALIZED FOR DAYS 334-014
Φ_M/Φ_E
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
ΔR (A.U)
1964 1965
01 030 060 090 120 150 180 250 DAY OF YEAR
NORMALIZED FOR DAYS 137-193
1.05
1.00
0.95
-15.7%/A.U.
Φ_M/Φ_E
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
ΔR(A.U.)

Figure 7



G68-952-1
MARINER IV
DET. C (PERCENT)
100
90
80
70
R (A.U.)
1.4
1.2
1.0
HELIOCENTRIC
RADIAL
DISTANCE
MARINER IV
DEEP RIVER NEUTRON MONITOR 5 DAY AVERAGES
N.M. (PERCENT)
100
95
90
SMOOTHED SUNSPOT NUMBERS
30 DAY RUNNING AVERAGE
PER 5 DAYS
SUNSPOT NUMBER
500
300
100
316 0 100 200 300 1 100 200 300 1 100 200 300
1964 1965 1966 1967
DAY OF YEAR

Figure 8

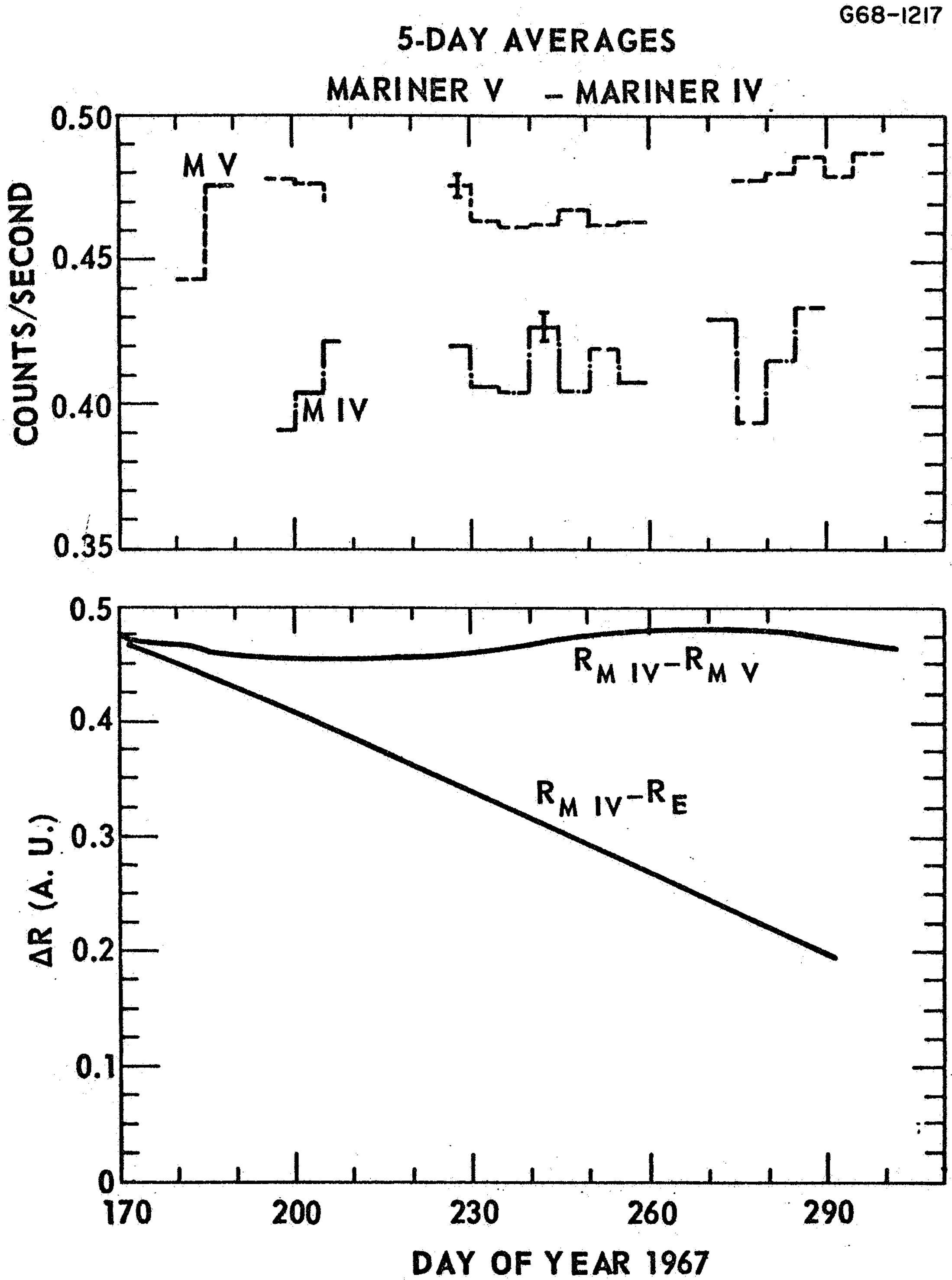

G68-1217
5-DAY AVERAGES
MARINER V – MARINER IV
COUNTS/SECOND
0.50
0.45
0.40
0.35
M V
M IV
ΔR (A. U.)
0.5
0.4
0.3
0.2
0.1
0
R M IV – R M V
R M IV – R E
170
200
230
260
290
DAY OF YEAR 1967

Figure 9