approached the planet at 4.5 km/sec from a local time of 0946 and nearly in the plane of Mars's orbit (Fig. 1). Mars's orbit is inclined 1°51′ to the ecliptic, and its equatorial plane makes an angle of 25°12′ with its orbital plane. On 14 July, Mars's north pole was tipped in the direction of orbital motion and toward the sun so that the subsolar point lay at 15.3°N latitude. Mars was 216×10^6 km from Earth, 232×10^6 km from the Sun (1.55 AU), and the Earth-Sun-Mars angle was 64°. The spacecraft passed over Mars's southern hemisphere. Shortly after the time of closet approach, it passed behind the planet as seen from Earth ("occultation"), but without entering the shadow of the planet. Some useful trajectory parameters appear in Table 1.

The fields-and-particles experiments were turned off during picture transmission from 1154, 15 July, to 2 August. Interplanetary results obtained before encounter and after 2 August will not be reported now.

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3. The Mariner IV project was managed by JPL/CIT for NASA under contract NAS7-100.

16 August 1965

Absence of Martian Radiation Belts and Implications Thereof

Abstract. *A system of sensitive particle detectors on Mariner IV showed the presence of electrons of energy* (E_e) *less than 40 kiloelectron volts out to a radial distance of 165,000 kilometers in the morning fringe of the earth's magnetosphere but failed to detect any such electrons during the close encounter with Mars on 14–15 July 1965, at the time when the minimum areocentric radial distance was 13,200 kilometers. This result can mean that the ratio of the magnetic dipole moment of Mars to that of the earth* (M_M/M_E) *is surely less than 0.001 and probably is less than 0.0005. The corresponding upper limits on the equatorial magnetic field at the surface of Mars are 200 and 100 gammas, respectively. It appears possible that the solar wind interacts directly with the Martian atmosphere.*

There is not yet a quantitative theory of the origin of the earth's radiation belts despite a large body of observational knowledge on (i) the distributions and energy spectra of the constituent particles and the time variations thereof; (ii) the geomagnetic field and its variations; (iii) natural radio waves in the ionosphere; (iv) the atmosphere of the earth; and (v) the solar wind in its vicinity. Thus it is clearly impossible to predict the detailed nature of the radiation belts of a planet of arbitrary magnetic moment at an arbitrary distance from the sun. Nonetheless it is apparent that the planet must be magnetized sufficiently strongly and it must be exposed to the flow of hot, ionized gas from the sun (the solar wind) in order that it have radiation belts resembling those of the earth. Under the latter requirement we are neglecting the minor component of the earth's radiation belts due to the radioactive-decay products of cosmic-ray-produced neutron albedo. Since the earth at 1.0 AU (astronomical unit, or 1.495985×10^8 km) and Jupiter at 5.2 AU from the sun both have intense radiation belts it is reasonable to expect that Mars at the intermediate distance of 1.52 AU has radiation belts also, *if it is a sufficiently magnetized body*. The criterion for sufficiency, in approximate terms, is that the outward pressure of the planet's magnetic field ($B^2/8\pi$) equals the inward dynamic pressure of the solar wind (nmv^2) at a radial distance R exceeding that to the top of its appreciable atmosphere. In the foregoing, B denotes the magnetic field strength ($B \sim M/R^3$); and n is the number density of charged particles of mass m and directed velocity v in the solar wind. In the case of the earth (magnetic dipole moment $M_E = 8.06 \times 10^{25}$ gauss cm^3), the stagnation point occurs at a radial distance of some 65,000 km on its sunward side.

Understanding of the configuration of the external magnetic field of a planet subjected to the flow of the solar wind dates from the classical theoretical work of Chapman and Ferraro in the 1930's. In recent years, this understanding has been improved by advances in the theory and endowed with detailed physical validity by a large variety of satellite and space-probe observations.

Not so clearly anticipated by the theory have been the observational findings (*1–3*) of the presence of electrons having energies of the order of tens of kev in the transition region between the (hypersonic) shock front and the magnetopause, and in the magnetospheric tail (in addition to the now well-known distribution of durably trapped electrons and protons interior to the magnetopause).

Outside of the shock front, the presence of the earth is undetectable by either magnetic measurements (*4*) or particle measurements (*2*). Within the transition region, there are turbulent magnetic fields of the order of 30 gammas (1 gamma = 10^{-5} gauss) (*5*) and an irregular distribution of electrons having energies from ~1 kev to some tens of kev. Interior to the magnetopause, there are regular magnetic fields and large intensities of durably trapped electrons and protons of energies up to several Mev.

On the strength of this massive observational knowledge of the earth's environment and of supporting theoretical considerations (*6*), it is assumed here that the appearance of detectable intensities of electrons having energies of some tens of kev is an inevitable and universal consequence of the quasi-thermalization of the solar wind (collisionless conversion of directed kinetic energy into random kinetic energy) as its forward motion is arrested by impact against a planetary magnetic field.

To the extent that this assumption is valid, a sensitive magnetometer and a sensitive detector of low-energy electrons are equivalent devices for the detection of a planetary magnetic field.

The search for radiation belts of Venus and of Mars was proposed in detail by us in 1959. Our simple low-energy-electron detector was carried on Mariner II which flew past Venus on 14 December 1962 at a minimum radial distance of approach of 41,000 km on the sunward side of the planet. No planetary effect was detected. This negative result was originally interpreted (*7*) to mean that the ratio of the magnetic dipole moment of Venus to that of the earth $M_V/M_E \leqq 0.18$. A recent reinterpretation based on subsequently increased knowledge of particle distributions in the earth's transition region, suggests $M_V/M_E \leqq 0.1$ (*8*).

The University of Iowa "package" of low-energy-particle detectors on Mariner IV comprises three end-window Geiger-Mueller tubes (EON type 6213), designated A, B, and C, and one thin (35-micron) surface-barrier solid-state detector (Nuclear Diodes, Inc.) having two discrimination levels, designated D_1 and D_2. Each of the four detectors has a conical collimator with a full vertex angle of 60° (nominal). The axes of the collimators of B, C, and D are parallel to each other and at an angle of 70° to the roll axis of the spacecraft, and the axis of the collimator of A is at an angle of 135°. The roll axis of the spacecraft is directed continuously at the sun with an error of less than 1°; rotation of the spacecraft about this axis is controlled so that the axis of a spacecraft-fixed, directional antenna is pointed approximately toward the earth. Thus, detectors B, C, and D receive particles moving generally outward from the sun and at angles to the sun-to-probe vector of 70° ± 30°. The detectors themselves and the complete inner walls of their collimators are shielded from direct light and x-rays from the sun. Detector A receives particles moving generally inward toward the sun at angles to the sun-to-probe vector of 135° ± 30°. The sidewall shielding of all detectors has a minimum thickness corresponding to the range of ~50-Mev protons. Both discrimination levels of the solid-state detector, D_1 and D_2, are insensitive to electrons of any energy in the intensities found in the present series of experiments. This insensitivity is designed into the system (thin detector, high bias level, and 200-nsec delay-line pulse-clipping) and was demonstrated in thorough testing prior to flight. It was further confirmed during traversal of the magnetosphere in the early phase of the flight of Mariner IV (*9*). Detector channels D_1 and D_2 are also insensitive to galactic cosmic rays. In order to have direct observational knowledge of the proper operation of these channels during interplanetary flight, the solid-state detector is equipped with an ${}_{95}AM^{241}$ source of ~5.5-Mev alpha particles

Table 1. Characteristics of detectors.

Detector	Geometric factor: Unidirectional (cm² sterad)	Geometric factor: Omnidirectional (cm²)	Particles to which sensitive: Electrons (E_e)	Particles to which sensitive: Protons (E_p)	Dynamic range
A	0.044 ± .005	~ 0.15	≳ 45 kev	>670 ± 30 kev	From galactic cosmic ray rate of 0.6 to 10^7 count/sec
B	.055 ± .005	~ .15	≳ 40 kev	>550 ± 20 kev	As for A
C	.050 ± .005	~ .15	≳ 150 kev	>3.1 Mev	As for A
D_1	.065 ± .003		None	$0.50 \leqq E_p \leqq 11$ Mev	From inflight source rate to 10^6 count/sec
D_2	.065 ± .003		None	$0.88 \leqq E_p \leqq 4.0$ Mev	As for D_1

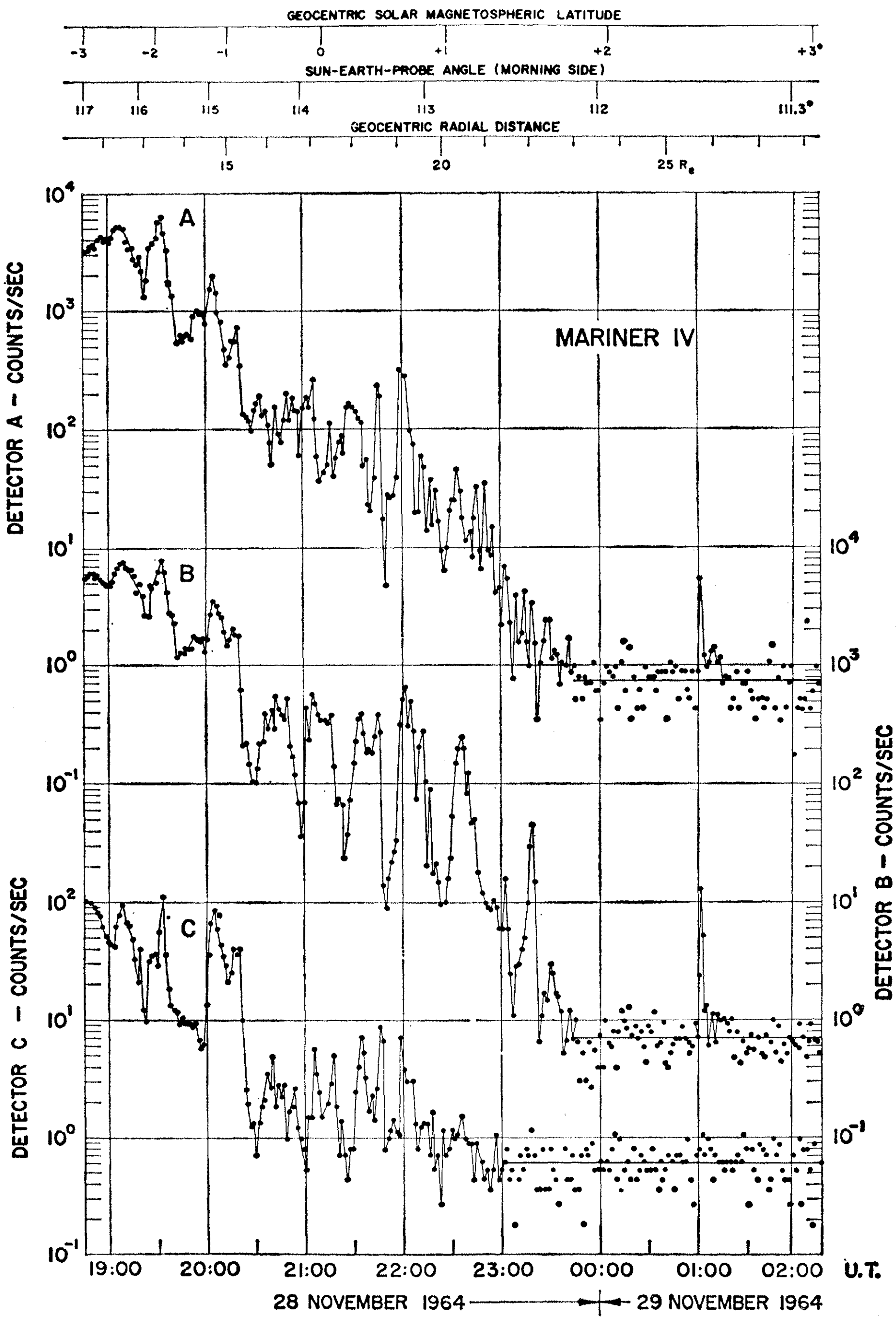


Fig. 1. Counting rates of detectors A, B, and C on Mariner IV during outward traversal of earth's magnetosphere.

which provides in-flight counting rates of 0.071 and 0.059 sec^{-1} on D_1 and D_2, respectively—rates which are accurately identical to their values before launch.

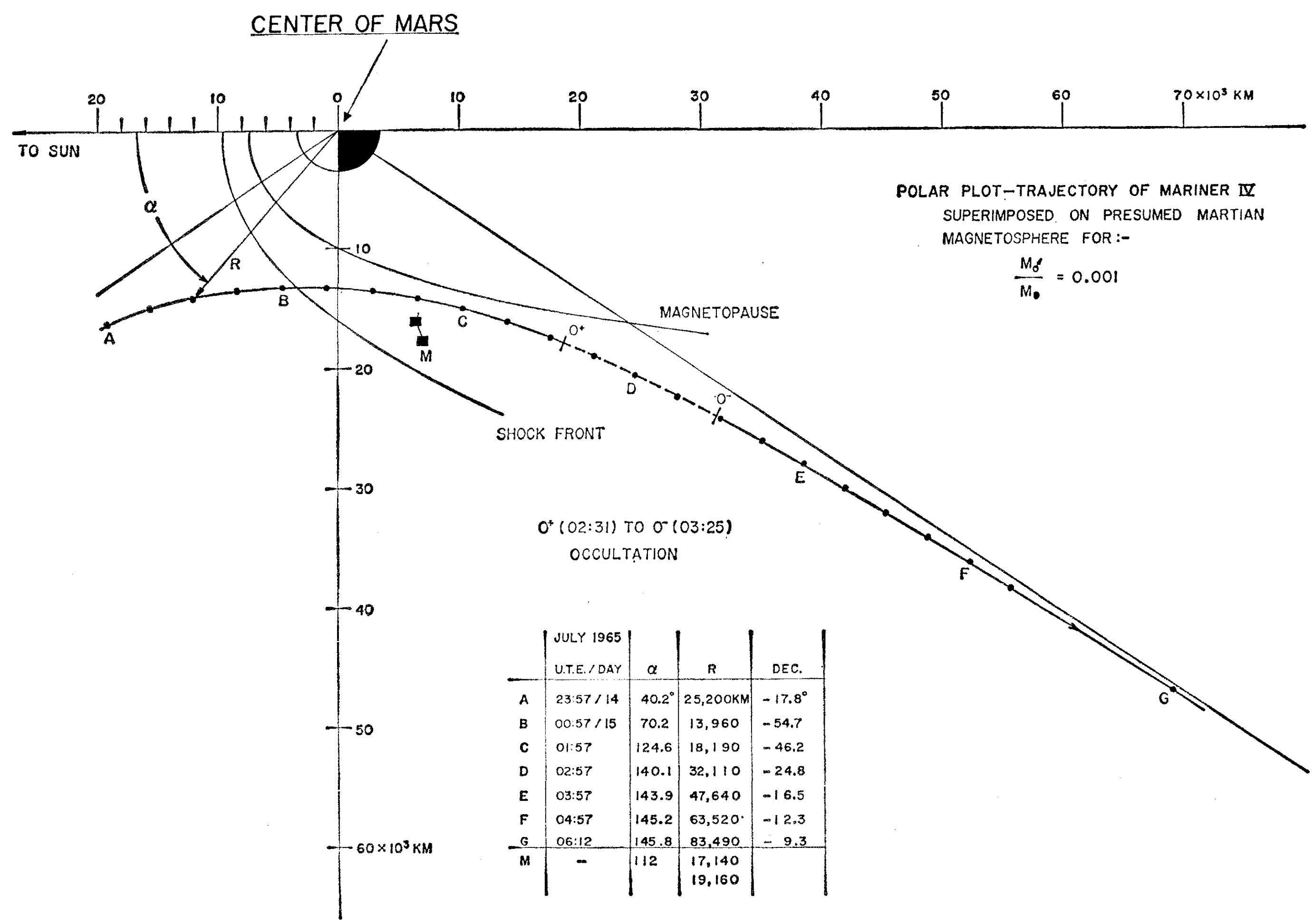
The counting rate of each of the three Geiger tubes is the sum of the rates due to galactic cosmic rays (about 0.6 count/sec); to electrons, x-rays, protons, alpha particles, and other particles, which pass through their collimators; and, in some cases, to sidewall penetrations.

Further details concerning the detectors are given in Table 1. Combinations of the data from this simple system of detectors provide information on absolute intensities, particle identification, energy spectra, and angular distributions. In favorable cases particle identification is conclusive.

The five University of Iowa data channels are part of a commutated sequence of eight as follows: E, B, D_1, D_2, E, B, A, C (where E represents the data channel from another experiment). The basic frame of telemetry during the "cruise mode" (8.33 bit/sec for entire spacecraft), which was employed throughout the period of the present study, is of 50.4-second duration. Unscaled counts from each of the detectors corresponding to the above eight channels are gated in turn into a shift register of 19 bits plus 2 overflow bits for a 45.0-second period and are read out through the spacecraft telemetry system during the subsequent 5.4 seconds. A complete cycle of eight detectors is completed each 8 × 50.4, or 403.2 seconds. Thus the "duty cycle" of each of the four channels A, C, D_1, and D_2 is 11.2 percent and that of channel B is 22.3 percent.

Outward Passage through the Earth's Magnetosphere. Of the four detectors in our (University of Iowa) equipment, the low-energy-electron detectors, A and B, are the most sensitive for the detection of the outer fringes of a magnetosphere.

The outward traversal of the earth's magnetosphere by Mariner IV on 28–29 November 1964 provides a basic calibration of the capabilities of the system and the direct foundation for the interpretation of the observations during the Martian encounter. The responses of detectors A, B, and C during the traversal of the morning fringe of the earth's magnetosphere are shown in Fig. 1. The intensity of protons $0.5 \leq E_p \leq 11$ Mev (D_1) drops to an undetectable level at a radial distance of 10.5 R_E (earth radii) (*9*)—not shown in Fig. 1—but electrons of energy $E_e > 40$ kev are detected continuously out to 23 R_E and there is an outlying intensity spike at 25.7 R_E. The unidirectional geometric factors of detectors A and B on Mariner IV (Table 1) are over 20 times as great as those of similar low-energy-electron detectors used by this laboratory in Explorer XIV (*10*) and OGO-I and by Anderson *et al.* (*3*) in IMP's I, II, and III (interplanetary monitoring plat-



	JULY 1965 U.T.E./DAY	α	R	DEC.
A	23:57/14	40.2°	25,200KM	-17.8°
B	00:57/15	70.2	13,960	-54.7
C	01:57	124.6	18,190	-46.2
D	02:57	140.1	32,110	-24.8
E	03:57	143.9	47,640	-16.5
F	04:57	145.2	63,520	-12.3
G	06:12	145.8	83,490	- 9.3
M	-	112	17,140 19,160	

Fig. 3. An analytical diagram used for inferring an upper limit to the ratio of the magnetic dipole moment of Mars to that of the earth. Successive black dots on the trajectory are at 15-minute intervals.

forms). Their omnidirectional geometric factors are, however, about the same. Hence the detectors on Mariner IV have a 20-fold increase in "signal-to-noise ratio" for the detection of electrons having energies of the order of some tens of kev.

We noted that the outermost detectable limit of the earth's magnetosphere (25.7 R_E at a Sun-Earth-probe angle of 112°) as shown by our detectors A and B is nearly the same as that reported by Ness *et al.* (*4*) with the IMP-I magnetometer.

Encounter with Mars. The Martian encounter occurred on 14–15 July 1965, after 228 days of interplanetary flight during which our apparatus operated properly and provided a large volume of data on solar proton and electron events (*11*).

Every data point from each of the detectors A, B, C, D_1, and D_2 is shown in Fig. 2 for the time period 1000 U.T.E. of 14 July 1965 to 1154 U.T.E. of 15 July 1965, together with scales of areocentric latitude and areocentric radial distance *R*. The abbreviation U.T.E. means Universal Time Earth, that is, the Greenwich Mean Time of reception of the data at the earth; the data were recorded at the spacecraft 12.0 minutes earlier. Areocentric latitude is measured positive north and negative south from the equatorial plane of the planet (the plane through its center perpendicular to its axis of rotation). Closest approach of Mariner IV to the center of Mars, areocentric radial distance 13,200 km, occurred at 0113 U.T.E. of 15 July. During the period 0231 to 0325 U.T.E. of 15 July the spacecraft, as viewed from the earth, was occulted by Mars and no signals were received.

Prior to 1520 U.T.E. of 14 July the counting rates of all detectors were indistinguishable from their long-term interplanetary background values. At 1520 (±10) U.T.E. the rates of D_1, D_2, and B began to depart from their background values and continued clearly above background until spacecraft "science" was turned off at 1154 U.T.E. of 15 July. The effect was weak or absent on detectors A and C. The particles responsible for the effect are identified conclusively as protons (or other heavy particles) with an energy spectrum which falls steeply between 0.5 and 0.9 Mev. At the time of onset of the effect, the spacecraft was 162,000 km from the center of the planet at a Sun-Mars-probe angle of 34°. It is concluded that the observed protons are not associated with Mars on the following grounds:

1) The time (and spatial) dependence of the intensity as measured along the trajectory of the spacecraft is quite different from that expected in a planetary radiation belt.

2) No such intensities of protons are found beyond about 65,000 km from the earth in any direction; and, as will be shown below, the particle populations much nearer to Mars are vastly less than those at similar distances from the earth.

3) Both observationally and theoretically the outer fringe of a planetary magnetosphere is characterized by energetic electrons, not by protons.

4) The time history, proton intensity, and proton spectrum observed on 14–15 July are all similar to those commonly observed in interplanetary space remote from any celestial body. Five events of this nature were observed during the 2 weeks before the Martian encounter period.

For the above reasons, the observed protons on 14–15 July are identified as a "solar proton event" whose appearance during this period was coincidental with the Martian encounter.

Throughout the remainder of the encounter period, there was no further significant departure from background rates by any one of the five detector channels, A and B being presumably the most sensitive to the fringe of a magnetosphere.

Thus, no particle effects whatever, attributable to Mars, were detected despite the close approach of the spacecraft.

More precisely, the unidirectional intensity of electrons $E_e > 40$ kev did not exceed 6 (cm^2 sec sterad)$^{-1}$ over any 45-second sampling period. A similar trajectory past the earth would have encountered unidirectional intensities as high as 10^7 (cm^2 sec sterad)$^{-1}$ (*12*). Hence, as a purely observational matter it is clear that the radiation environment of Mars is vastly different from that of the earth.

Implications of the Absence of Radiation Belts. Assuming the applicability of the composite theoretical-observational knowledge of the magnetospheric transition region around the earth (described above) to that of a planet of much smaller magnetic moment, we can use our negative results to place an upper limit on the magnetic moment of Mars.

The basic scaling law (*13*) is given by

$$nmv^2 \approx B^2/8\pi \approx M^2/R^6. \quad (1)$$

It is further supposed that *v* at Mars is the same as at the earth and that *n* is an inverse square function of heliocentric radial distance. Thus, it is supposed that the shock front and the magnetopause have the same geometric shapes as for the earth with the linear scale factor

$$R_M/R_E = 1.1\ (M_M/M_E)^{\frac{1}{3}}. \quad (2)$$

It is known that the shock front and the magnetopause have approximately cylindrical symmetry about the Sun-planet line, more or less independent of the orientation of the magnetic moment of the planet.

The application of these ideas to the present situation is described by Fig. 3. The curved line ABCDEFG represents the encounter trajectory of Mariner IV in areocentric polar coordinates *R* (radial distance from center of Mars) and α (Sun-Mars-probe angle). The cross section of the body of the planet is shown to the same scale. Data for the trajectory plot are from Jet Propulsion Laboratory's "IBSYS-JPTRAJ-SFPRO 062965 Mariner IV Mission Encounter Fine Print 0310 GMT 15 July 61 Special," which is the first-order-corrected, post-encounter ephemeris, believed to be in error by less than 100 km. Adopting a blended best fit to present knowledge of the geometric forms of the earth's shock front and magnetopause (*2, 4, 14*), we have drawn in Fig. 3 geometrically similar curves scaled according to Eq. 2 for the case $M_M/M_E = 0.001$. The two connected squares labeled *M* are similarly transformed points from Fig. 1 which represent the positions of easily detectable intensities of electrons $E_e >$ 40 kev at 23.0 and 25.7 R_E, respectively, in the fringe of the earth's magnetosphere on 28–29 November 1964.

We conclude from Fig. 3 that M_M/M_E is surely less than 0.001. In fact, a literal interpretation of Fig. 3 gives $M_M/M_E < 0.0005$. In view of the wide ranges of areocentric latitude and of α while the spacecraft was flying more or less parallel to the scaled magnetopause, these conclusions are probably valid for any orientation of the Martian magnetic moment.

The foregoing results mean that the equatorial surface magnetic field of Mars is less than 200 (and perhaps 100) gammas (radius = 3417 km), and hence they suggest that the solar wind will, on occasion and perhaps usually, have a direct interaction with the Martian atmosphere. This interaction may be of essential importance in determining the physical state of the atmosphere.

Also, it is evident that the Martian atmosphere and surface are exposed to the full effects of solar and galactic cosmic radiation irrespective of latitude.

The observed weakness of the Martian magnetic field will presumably contribute to the understanding of the internal structure of the planet, though we do not pretend competence in this field and make only a few general remarks. It is noted that the origin of the earth's general magnetic field is not understood on the basis of a priori theory and that no significant prediction of the magnetic moment of any other celestial body exists. On the basis of the most widely accepted conjecture on the physical origin of the geomagnetic field, primarily due to Bullard and to Elsasser [the subject is reviewed by Elsasser (*15*) and by Cowling (*16*)], it is believed necessary that a planetary body be endowed with both rotation and a liquid, electrically conducting core in order that its externally apparent magnetization exceed the mean of

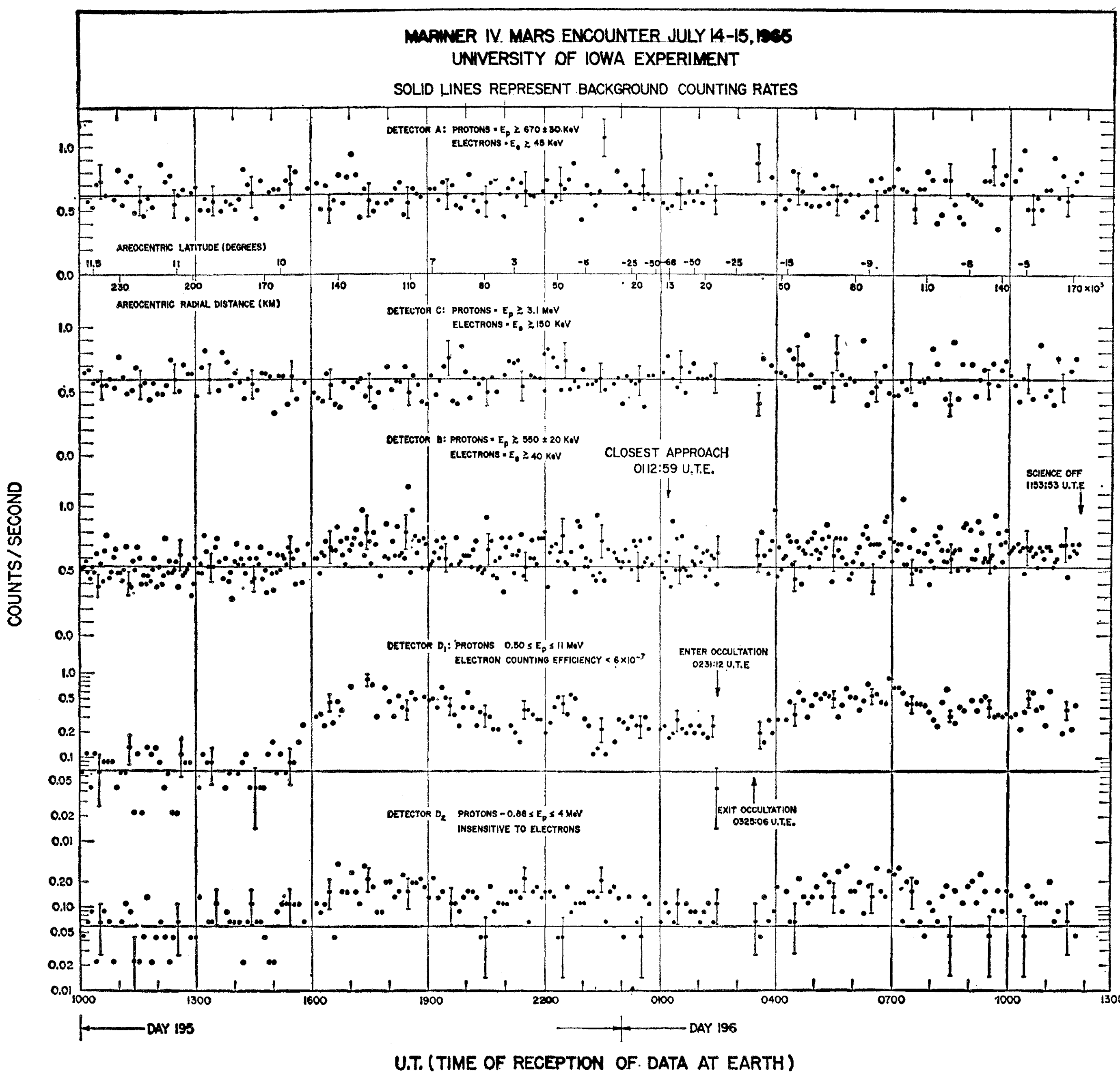


Fig. 2. A comprehensive plot of the counting rates of detectors A, C, B, D_1, and D_2 before, during, and after the encounter with Mars on 14–15 July 1965. Note scale of positional coordinates of the spacecraft in upper part of the figure.

the remanent values of its constituents. The mass of Mars is 0.107 that of the earth, its mean density is 3.95 g cm^{-3} (0.71 that of the earth and 1.18 that of the moon), and its radius is 0.536 that of the earth and 1.97 that of the moon (*17*). But since the period of rotation of Mars, 24.62 hours, is nearly the same as that of the earth, it appears that its vastly weaker magnetic moment must be attributed to such a markedly different internal structure or composition, or both, that it does not possess a liquid, electrically conducting core.

Some years ago Blackett (*18*) wrote as follows: "It has been known for a long time, particularly from the work of Schuster, Sutherland and H. A. Wilson, though lately little regarded, that the magnetic moment P and the angular momentum U of the earth and sun are nearly proportional, and that the constant of proportionality is nearly the square root of the gravitational constant G divided by the velocity of light c. We can write, in fact,

$$P = \beta \frac{G^{\frac{1}{2}}}{c} U, \quad (4)$$

where β is a constant of the order of unity."

He (*18, 19*) considered available evidence on the angular momenta and magnetic moments of the earth, of the sun, and of five stars and was led to the following: ". . . It is suggested tentatively that the balance of evidence is that the above equation represents some new and fundamental property of rotating matter. Perhaps this relation will provide the long-sought connexion between electromagnetic and gravitational phenomena."

Blackett's hypothesis has continued to be of interest, despite the fact that it has not gained general acceptance. The present experiment on the magnetic moment of Mars provides, perhaps, the first conclusive test of the hypothesis:

The ratio of the angular momentum of Mars to that of the earth is ~0.03 and by Blackett's Eq. 4 (*18*) this is also the predicted ratio of M_M/M_E, a value which is some 30 times larger than the upper limit which we have inferred from the observational evidence.

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12 August 1965

Search for Trapped Electrons and a Magnetic Moment at Mars by Mariner IV

Abstract. *The Mariner IV spacecraft on 14–15 July 1965 passed within 9850 kilometers of Mars, carrying a solid-state charged-particle telescope which could detect electrons greater than 40 kiloelectron volts and protons greater than 1 million electron volts. The trajectory could have passed through a bow shock, a transition region, and a magnetospheric boundary where particles could be stably trapped for a wide range of Martian magnetic moments. No evidence of charged-particle radiation was found in any of these regions. In view of these results, an upper limit is established for the Martian magnetic moment provided it is assumed that the same physical processes leading to acceleration and trapping of electrons in Earth's magnetic field would be found in a Martian magnetic field. On this basis, the upper limit for the Martian magnetic moment is 0.1 percent that of Earth for a wide range of postulated orientations with respect to the rotational axis of Mars. The implications of these results for the physical and biological environment of Mars are briefly discussed.*

Whether Mars has a general magnetic field—and consequently trapped radiation—is relevant to understanding the origin and evolution of Mars. Prior to this time there were no measurements of the magnetic fields or charged-particle radiation in the vicinity of the planet; hence any experiments which could detect a planetary field or charged-particle radiation are of intense physical and biological interest. The first opportunity to approach Mars came on 14–15 July 1965 when the Mariner IV spacecraft passed within 9850 km of the planetary surface. Two kinds of measurements were made which bear on the presence of planetary magnetic fields: namely, magnetometer observations (*1*) and charged-particle radiations of which we report here measurements from the University of Chicago instrument on the space probe.

To understand the relevance of charged-particle radiation to the existence of a planetary magnetic field we recall that the general field of Earth traps charged particles in radiation belts extending to the outer boundary between the geomagnetic field and the solar wind. Evidence now appears to be conclusive that, given these conditions, a planetary magnetic field will also lead to the buildup of locally accelerated particles within the magnetic field and that this trapped radiation will be present continuously, although the flux is highly variable in time. In addition, the supersonic solar wind and the interplanetary magnetic field which it contains interact with the magnetosphere to produce a bow shock at a characteristic stand-off distance beyond the magnetosphere (Fig. 1) (*2*). Associated with the bow shock are