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,

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

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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References and Notes

1. J. W. Freeman, J. A. Van Allen, L. J. Cahill, *J. Geophys. Res.* **68**, 2121 (1963); C. Y. Fan, G. Gloeckler, J. A. Simpson, *Phys. Rev. Letters* **13**, 149 (1964); L. A. Frank, *J. Geophys. Res.* **70**, 1593 (1965).
2. L. A. Frank and J. A. Van Allen, *J. Geophys. Res.* **69**, 4923 (1964).
3. K. A. Anderson and H. K. Harris, *Trans. Amer. Geophys. Union* **46**, 119 (1965); ———, R. J. Paoli, *J. Geophys. Res.* **70**, 1039 (1965).
4. N. F. Ness, C. S. Scearce, J. B. Seek, *J. Geophys. Res.* **69**, 3531 (1964).
5. L. J. Cahill and P. G. Amazeen, *ibid.* **68**, 1835 (1963).
6. F. L. Scarf, W. Bernstein, R. W. Fredricks, *ibid.* **70**, 9 (1965).
7. L. A. Frank, J. A. Van Allen, H. K. Hills, *Science* **139**, 905 (1963).
8. J. A. Van Allen, private communication.
9. S. M. Krimigis and T. P. Armstrong, *Trans. Amer. Geophys. Union* **46**, 113 (1965).
10. L. A. Frank, J. A. Van Allen, E. Macagno, *J. Geophys. Res.* **68**, 3543 (1963).
11. J. A. Van Allen and S. M. Krimigis, *Trans. Amer. Geophys. Union* **46**, 532 (1965).
12. L. A. Frank, J. A. Van Allen, H. K. Hills, *J. Geophys. Res.* **69**, 2171 (1964).
13. J. R. Spreiter and W. P. Jones, *ibid.* **68**, 3555 (1963).
14. J. P. Heppner, N. F. Ness, C. S. Scearce, T. L. Skillman, *ibid.*, p. 1.
15. W. M. Elsasser, *Rev. Mod. Phys.* **22**, 1 (1950).
16. T. G. Cowling, *Magnetohydrodynamics* (Interscience, New York, 1957).
17. C. W. Allen, *Astrophysical Quantities* (Athlone Press, London, 1955).
18. P. M. S. Blackett, *Nature* **159**, 658 (1947).
19. ———, *Phil. Mag.* **40**, 125 (1949).
20. Development, construction, and preflight testing of the University of Iowa equipment on Mariner IV was supported by subcontract 950613 with the Jet Propulsion Laboratory. We thank T. P. Armstrong, D. L. Chinburg, and D. C. Enemark of the University of Iowa; and Dr. H. R. Anderson, R. K. Sloan, R. A. Lockhart, and D. Schofield of the Jet Propulsion Laboratory for help with various aspects of the work. The flight data used here are from the J.P.L. preliminary—though substantially complete—"users programs," which have been received promptly. Reduction and analysis of the data have been supported in part by NASA research grant NsG-233-62. S.M.K. and H.K.H. are graduate trainees of NASA.

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 bursts of electron fluxes found near the shock and beyond (Fig. 1, region 3) (*3*). Similar electron bursts are more densely distributed between the shock and the magnetospheric boundary (Fig. 1, region 2) (*4*). The trapped radiation distributed within the magnetospheric boundary constitutes a third electron region (Fig. 1, region 1). In what follows we assume that the same physical processes leading to acceleration and trapping of electrons in Earth's magnetic field would exist for any Martian dipole field. Thus there are three types of radiation "signatures," which could reveal the presence of a Martian magnetic field. Their relative locations would provide information on the magnitude of the Martian magnetic dipole moment.

We now report on a search for these three radiation signatures due to electrons greater than 40 kev—an energy range most likely, by analogy with Earth, to provide a sensitive test. The trajectory of Mariner IV provided a wide coverage of the possible charged-particle configurations around the planet. We find that there is no evidence for (i) a trapped radiation belt containing electrons greater than 40 kev energy, including electrons in the Mev energy range; (ii) electrons associated with a transition region between a bow shock and a magnetosphere; and (iii) electron spikes at a bow shock or at greater distances.

Normally, a planet with even a slight magnetic field might produce a wake extending in the antisolar direction from which some particle radiation might be expected to escape. The Mariner IV spacecraft did not pass through a possible Martian wake, but it did pass closely enough to have detected any substantial escape of electrons had such a wake existed. No effect was found.

If we introduce the simplifying assumption that the Martian magnetic field would be a dipole field, probably oriented in the direction of the spin axis of the planet, then we reach the following conclusions based on our observations:

1) There could not be a Martian dipole magnetic moment greater than

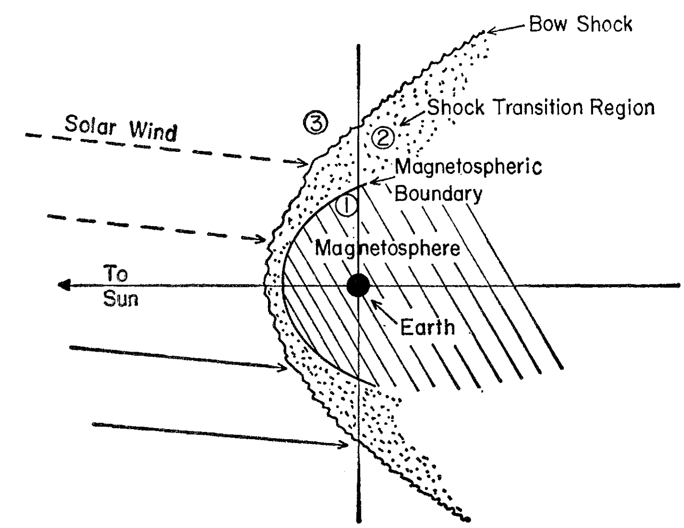
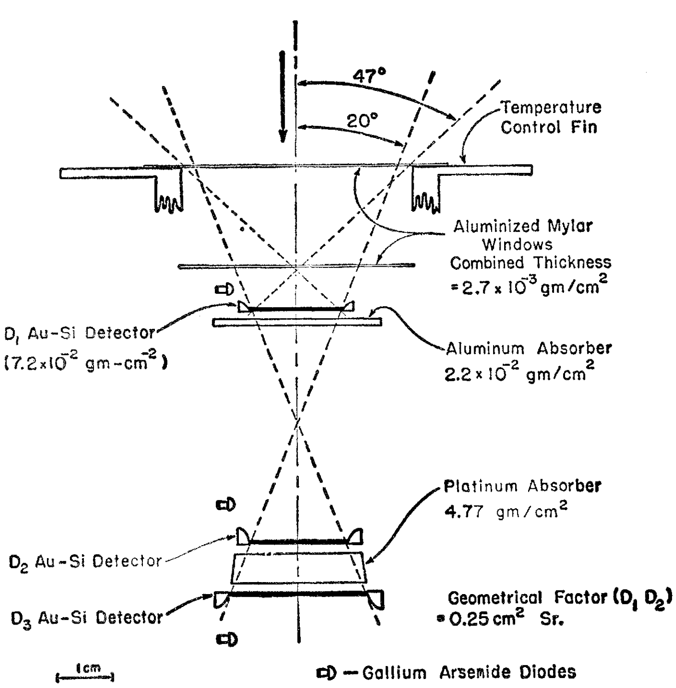
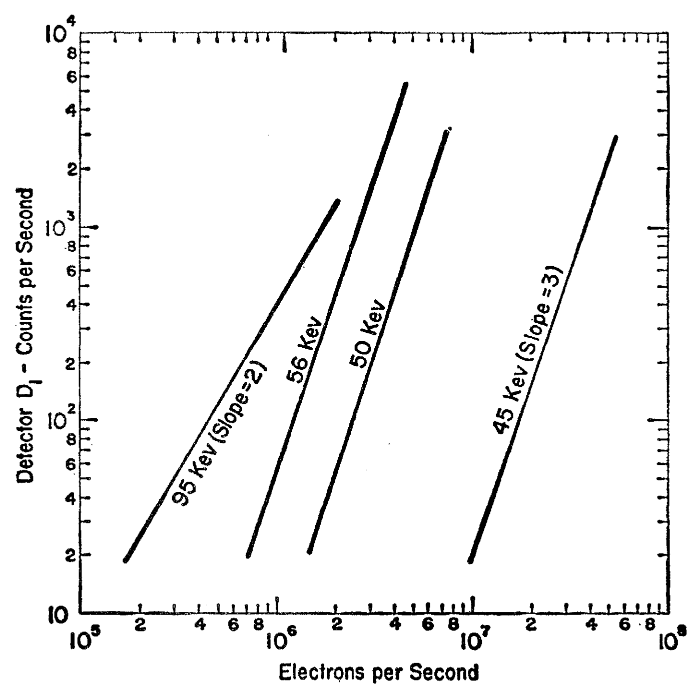


Fig. 1 (left). Relative location of electrons inside the magnetospheric boundary of Earth (*1*), the transition region (*2*), and outside the bow shock (*3*). The solar wind carries an interplanetary magnetic field of about 5 × 10^{-5} gauss.

Fig. 2 (below left). Cross-sectional view of charged-particle telescope. The main cone for particle acceptance is in the antisolar direction.

Fig. 3 (below). Calibrated response of the D_1 detector system for electrons. These curves are derived from laboratory measurements and take into account the aluminized-mylar window. The number of electrons required by pile-up to produce a count is given by the slope.





$2 \times 10^{-3} M_E$, where M_E is the present magnetic moment of Earth.

2) Since none of the three radiation signatures was observed it is very probable that the Martian dipole moment is substantially less than $10^{-3} M_E$.

These results have important implications for the physical and biological environment of Mars. For example, owing to the tenuous nature of the Martian atmosphere, as determined by the occultation experiment on board Mariner IV (5), the primary cosmic-ray flux reaches the entire surface of Mars; the generation of secondary particles through nuclear interactions takes place almost entirely below the surface of the solid planet.

The charged-particle telescope was designed to investigate charged-particle radiation in interplanetary space between the orbits of Earth and Mars and in the vicinity of Mars. The interplanetary experiments measured solar modulation of galactic proton and helium energy spectra and fluxes in the energy range 1 to 170 Mev per nucleon. Protons and helium nuclei from several solar flares, and 27-day recurring proton fluxes were studied. The instrument operated stably throughout the 228 days from launch to encounter with Mars and provided nearly continuous information over the entire period.

The following description of the instrument is limited to those characteristics of interest for the detection of charged particles near Mars. The telescope consists of three gold-silicon, surface-barrier detectors with aluminum and platinum absorbers as shown in the cross-sectional view of Fig. 2. The circular detectors, D_1 and D_2, have surface areas of 2.4 cm². The area of detector D_3 is 5 cm². Each detector has a silicon thickness of 500 μ, including a depletion depth (sensitive region) of 200 μ. Detectors D_1 and D_2 define an acceptance-cone angle of 40° for arriving charged particles. The geometrical factor for the arrival of low-energy particles at detector D_1 is 4 cm² sterad as determined by the geometry of the temperature control fin.

The axis of the acceptance-cone angle for charged particles is aligned with respect to the spacecraft so that it is always pointing away from the sun. The counting rates of charged particles fall into three intervals of particle energy. These energy intervals are determined by coincidence techniques. For example, particles which initiate pulses in D_1 but not in D_2 are designated $D_1\bar{D}_2$ events (including protons of 1 to ~15 Mev and electrons with energies as described below); particles which trigger both detectors D_1 and D_2 but not D_3 are designated $D_1D_2\bar{D}_3$ events; and so on. The number

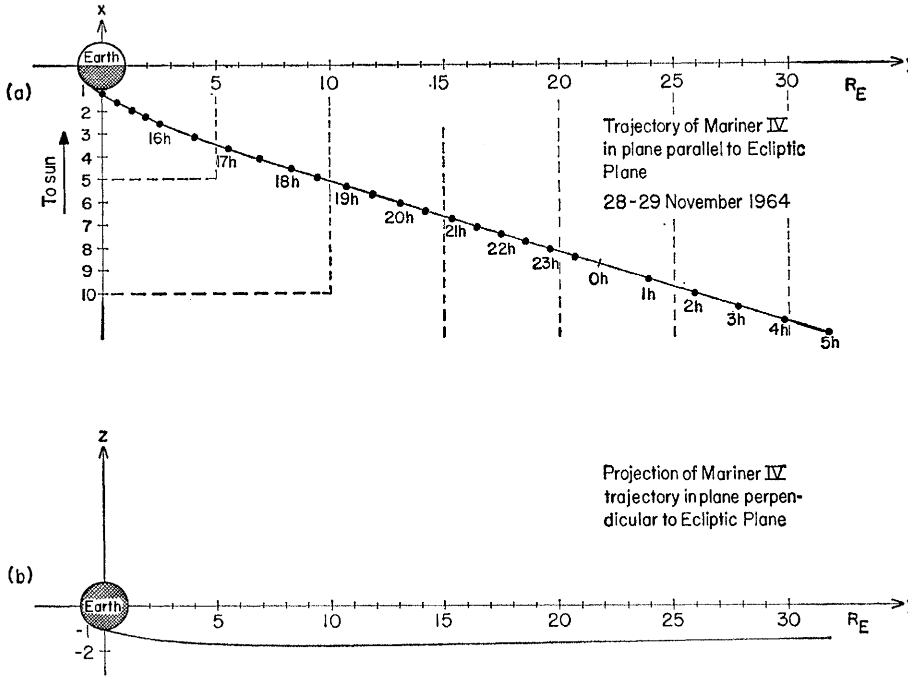


Fig. 4. The trajectory of Mariner IV away from Earth after launch, 28 November 1964. The coordinates are in units of Earth radii, R_E.

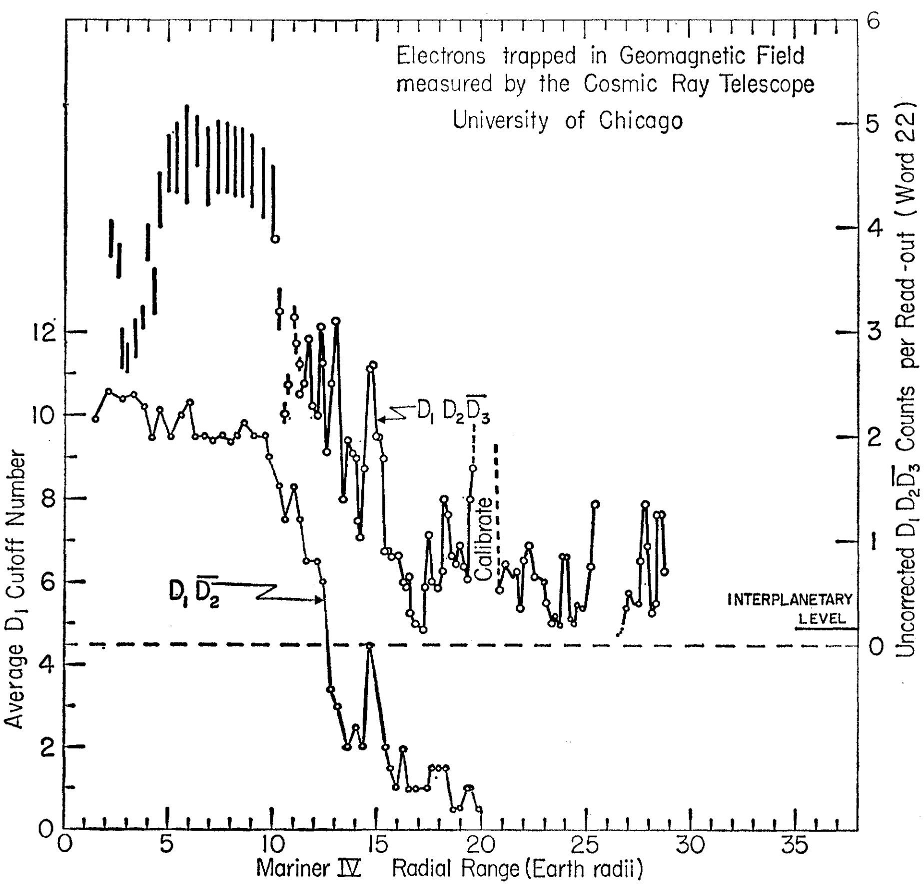


Fig. 5. The uncorrected counting rates of the $D_1\bar{D}_2$ and $D_1D_2\bar{D}_3$ channels for electrons in the geomagnetic field of Earth. For example, the peak at 18 R_E corresponds to about 400 count/sec for channel $D_1\bar{D}_2$.

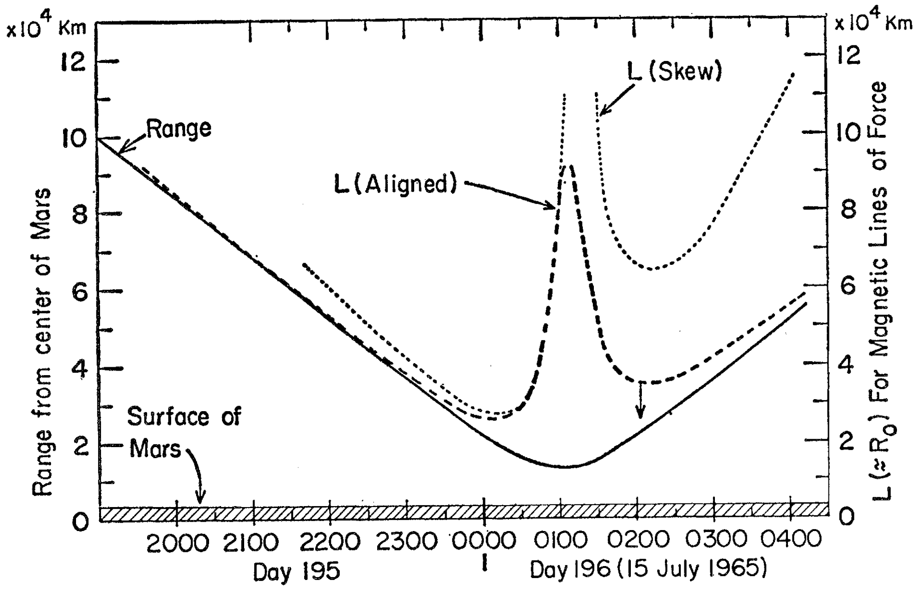


Fig. 6. Ordinate on left is the areocentric range of Mariner IV. Ordinate on right is equivalent to the equatorial radius of the line of magnetic force passing through the Mariner IV trajectory. Compression of the magnetic field by the solar wind lowers the second lobes of the "*L*" curves as shown by the arrow. Hours are in spacecraft time.

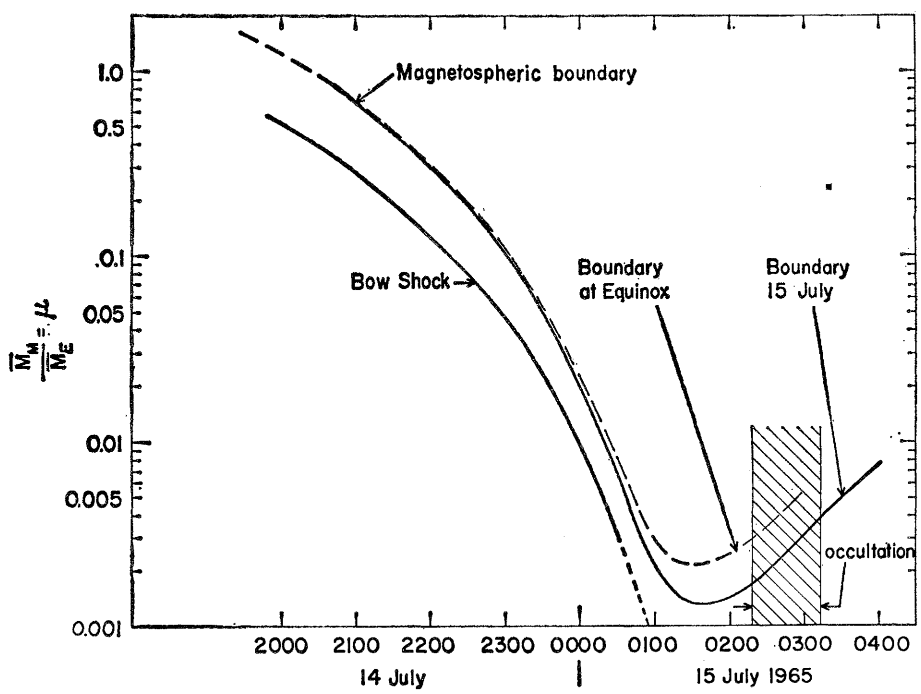


Fig. 7. Sensitivity for detection of Martian magnetic moment during encounter: M_M, Martian magnetic moment; M_E, Earth magnetic moment. On 15 July 1965 the arrival of the solar wind is 15° north of the Martian equator.

of events recorded in each of the three particle-range channels is read out periodically by the spacecraft data and telemetry systems. In addition, a 128-channel pulse-height analyzer in the instrument determines the pulse height in detector D_1 for the two higher particle-range intervals. The unique separation of protons from helium nuclei by this "energy loss and range" technique will not be described here. The complete instrument weighs 1.2 kg and requires 0.6 watt of power. The average information-bit rate for this experiment is 0.4 bit/sec. At periodic intervals the instrument is switched into a "calibrate" mode in order to check the performance of individual detectors.

Electrons are detected by the D_1 detector and the D_1D_2 detectors in coincidence. The aluminized-mylar window in front of the telescope established a low-energy limit of 40 kev for electron penetration. Above ~210 kev and up to several Mev energy, individual electrons are detected by D_1 with an efficiency exceeding 0.2. Below 210 kev electrons will be detected if the flux is high enough so that more than one electron arrives at the detector within the resolving time of the detector system. For electrons below ~100 kev we must also take into account both the energy dependence of electron transmission through the window (*6*), and the r.m.s. (root mean square) noise level of about 30 kev for the detector system. The response of a similar D_1 detector on the IMP I satellite to electrons in the vicinity of Earth's bow shock has been investigated (*3*) and a detailed investigation confirmed by laboratory electron accelerator studies is in preparation (*7*). The Mariner IV detector D_1 was identical with the IMP I detector except for its cross-sectional area and increased window thickness. In Fig. 3 we show the response curves calcu-

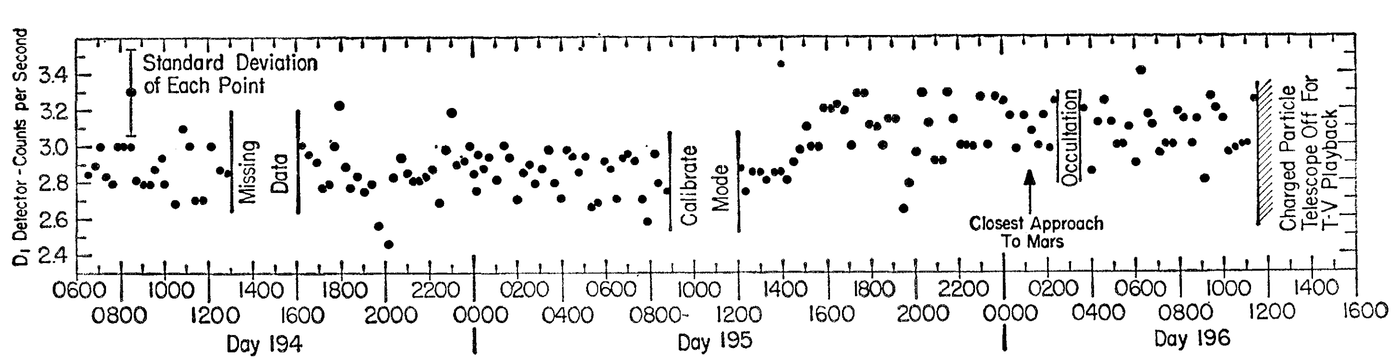


Fig. 8. Counting rates from the D_1 detector as a function of universal time. A small flux of low-energy interplanetary protons arrived at about 1500 U.T.

lated for the Mariner IV detector from the measured IMP I response.

As an example of the response of $D_1\bar{D}_2$ and $D_1D_2\bar{D}_3$ detector systems for electrons trapped within the geomagnetic field, we have obtained the data from the passage of Mariner IV through the geomagnetic field after launch on 28 November 1964. The trajectory projected in the plane of the ecliptic is shown in Fig. 4 where, by comparison with Fig. 1, we see that the trajectory passed the magnetospheric boundary at about 120° with respect to the Sun-Earth line and passed through the "dawn" side of the transition region behind Earth's bow shock. The electron data for the $D_1\bar{D}_2$ and $D_1D_2\bar{D}_3$ counting rate channels are shown in Fig. 5, not corrected for absolute flux levels. The instrument reaches saturation in the center of the outer Van Allen belt which extends (Fig. 5) out to approximately 10 R_E (units of Earth radii), but at greater distances the spatial and temporal structure of electron fluxes becomes clear. Typical electron "spikes" are observed in the transition region out to about 28 R_E. We note that on several occasions the counting rate between electron spikes in the transition region dropped to the interplanetary level in agreement with observations on IMP I (*3*).

With the knowledge of both the electron response of the telescope and the trajectory of the spacecraft relative to the planet Mars, we next explore the expected locations of characteristic electron signatures at Mars for a range of assumptions regarding the magnetic moment of Mars.

Models for Magnetic Fields and Particle Distributions. Not knowing the strength or orientation of a possible magnetic moment for Mars our objective is to examine the penetration of the Mariner IV trajectory into a wide range of possible model fields. In the discussion which follows we assume a magnetic dipole moment $\mathbf{M}_M$ located at the center of Mars. Our first task is to find the dipole lines of force which intersect the position of our detector as it passes through the assumed field. The identification of the lines of force on which a group of particles is moving is most conveniently specified (*8*) by a parameter *L* which, for a pure dipole, is equivalent to the equatorial radial distance R_0 from the dipole to the line of force on which the measurement is being made. For example, if the Mariner IV trajectory was confined to the equatorial plane of the dipole, the spacecraft range and the *L*-value for the magnetic line of force intersecting the spacecraft would be identical. However, since the spacecraft trajectory does not lie in the equatorial plane, the spacecraft range and the *L*-values are different. Electrons are most stably trapped in regions of small *L*-value. Clearly the minimum *L*-values reached during the traversal of Mars provide the most sensitive test for trapped radiation. In general this does not turn out to be the point of closest approach to the planet. The spacecraft trajectory passes from +10° to −68° magnetic latitude in its traversal of Mars. For the case $\mathbf{M}_M \parallel \varpi_M$ where ϖ_M is the spin axis vector for Mars, the equatorial equivalent range of lines of force intersecting the spacecraft as a function of spacecraft time (*9*) is shown by the dashed line in Fig. 6, if there is no compression by the solar wind (*10*). In Fig. 6 the minimum *L*-values occur near 0020 hour and 0200 hour, spacecraft time. To approximate the "worst case" we have tilted $\mathbf{M}_M$ by 40° in the plane which includes ϖ_M and the spacecraft at 0110 hour, as represented by the dotted line for *L* (skew) in Fig. 6.

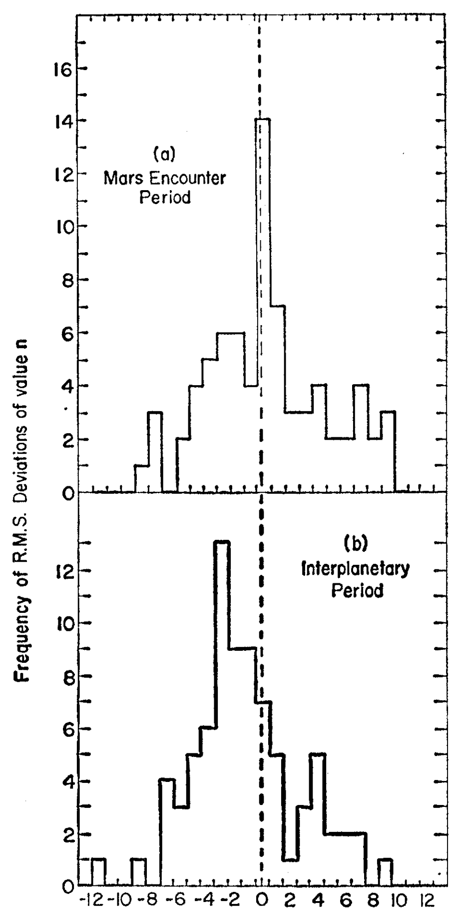


Fig. 9. *a*, 22 hours of data centered on time of closest approach to Mars; *b*, 24 hours of interplanetary data before "calibrate."

If now we introduce the solar-wind compression of the magnetic field on the sunward side as shown in Fig. 1 for Earth, the lines of force become distorted. This has the effect of lowering the second lobes of the *L*-value curves relative to the first lobes as indicated by the arrow in Fig. 6. Approximate solutions are not yet available for *L*-values from a compressed dipole field of arbitrary orientation with respect to the solar wind. The above considerations are independent of the value of $\mathbf{M}_M$.

Studies of the Earth's magnetosphere have shown that the location of the magnetospheric boundary is determined by a balance between the solar-wind pressure and that of the magnetic field; theoretical treatments for the cases of **M** perpendicular (*11*) and parallel (*12*) to the solar wind have served as a basis for our discussion. We extrapolated the measured density of the solar wind at Earth to Mars using the fact that it varies as the inverse square of the distance from the Sun. Furthermore the magnetospheric radius scales as the −1/6 power of the solar wind pressure. Thus if we call $R_{\text{mag-M}}$ and $R_{\text{mag-E}}$ the radial distance of the magnetospheric boundary at Mars and Earth respectively we obtain the approximate scaling law

$$R_{\text{mag-M}} = 1.16 \left(\frac{M_M}{M_E}\right)^{\frac{1}{3}} R_{\text{mag-E}}$$

In the following discussion we let $\mu = M_M/M_E$. With the given trajectory for Mariner IV we then obtain μ as an implicit function of the time at which Mariner IV crosses a Martian magnetospheric boundary over the range $\mu = 10^0$ to 10^{-3} as shown in Fig. 7 for $\mathbf{M}_M \parallel \varpi_M$. For small values of μ the magnetic latitude of incidence for the solar wind becomes important. This angle was 15° on 15 July 1965, and it lowers by a factor of 2 the detection range of $\mathbf{M}_M$ by Mariner IV.

From Fig. 7 and the lowering of the second lobe in Fig. 6, we conclude that the most sensitive time interval for the detection of trapped radiation along the Mariner IV trajectory lies between about 0140 hour and occultation.

The distance of the bow shock

Some Planetary and Orbital Characteristics of Mars*	
Mean distance from Sun	227.94×10^6km
Inclination of orbit from ecliptic plane	1° 51′
Inclination of equator from orbital plane	23° 59′
Eccentricity of orbit	0.093
Period of revolution about Sun	686.98 days
Period of rotation about axis	24 hours, 37 minutes
Equatorial radius	3380 km (0.53 times Earth radius)
Mass	0.108 times mass of Earth
Mean density	3.97 gm/cm^3
Surface acceleration due to gravity	376 gm/sec^2

* All values are from C. W. Allen, *Astrophysical Quantities* (Athlone Press, London, ed. 2, 1963).

R_b from the dipole is estimated in analogy with the observed conditions at Earth. If we take $R_{\text{mag-M}}$ along the Sun-Mars line, we assume $R_b = KR_{\text{mag-M}}$, with $K = 1.3$ for the shock stand-off distance. Figure 7 gives μ as a function of the time of passage through the shock. The results are uncertain for very small values of μ as shown by the dashed extension of the bow-shock curve.

We now apply the above considerations to the search for trapped radiation by making the assumption that the fundamental mechanism for particle acceleration and trapping observed in the earth's magnetosphere will scale down continuously over a reduction of more than 10^3 in equivalent magnetic moment. We note that before and during the measurements at Mars the interplanetary conditions were generally quiescent (*13*) with no significant magnetic storms which could have "dumped" the radiation which might be present. Therefore, the particle energy density U in the magnetic field B at Mars would be expected to rise to a value $U = A(B^2/8\pi)$, where A is less than 0.1 for electron energies more than 40 kev.

The boundary of the magnetosphere is determined by the balance of magnetic-field pressure and the solar-wind pressure: when the Sun-Mars-probe angle is large this field strength may lie in the range 20 to 80×10^{-5} gauss. Thus, inside but near the boundary we expect the omnidirectional electron flux to be of the order 10^4 to 10^5 electrons per square centimeter (for example, see the IMP I measurements with a detector similar to D_1, ref. *7*). Assuming an integral spectrum proportional to E^{-3} (E = kinetic energy) and the response of D_1 given by Fig. 3, we calculate that the expected counting rates for D_1 will be of the order 50 count/sec over the entire range of μ in Fig 7 *at the boundary*. By assuming a spectrum proportional to E^{-2} from the recent observations of Frank (*14*), our D_1 counting rate would be approximately 2000 count/sec. Substantial penetration inside the boundary to the minimum L-values for a given μ will further increase the flux levels by at least an order of magnitude. The above estimates take into account the fact that the traversal of minimum L-values for the magnetic field occurs at $-50°$ to $-30°$ magnetic latitude.

Since an increase of 0.7 count/sec could be detected in D_1 with 99-percent confidence when averaged over a single period of 16.7 minutes (equal to ten successive readouts of the telemetry word) we see that any crossing of a magnetospheric boundary would be detected. Additional flux enhancements would be observed inside the magnetosphere.

Observations at Mars. The D_1 counting rate was averaged for successive 16.7-minute intervals within which there were ten samples of approximately 0.3 minutes each. These data are presented in spacecraft time sequence in Fig. 8. It is apparent that the counting rate increased slightly and began fluctuating at about 1500 hour, 1.7×10^5 km away from the planet. The available evidence at present is against this increase in counting rate being associated with the planet. First, several small proton events have been observed by the charged-particle telescope in interplanetary space, especially within the 2-month period preceding encounter with Mars. Second, there seems to be no reasonable way in which this radiation could be associated with the planet, extend out to 1.7×10^5 km, and continue at roughly *the same level* until the end of transmission at 1148 hour on 15 July. For these reasons we assign a solar or interplanetary origin to this proton flux.

In Fig. 9 we compare the frequency of r.m.s. deviations about the means for (*a*) the Mars encounter period and (*b*) the interplanetary medium. There are no statistically significant differences in these distributions. These

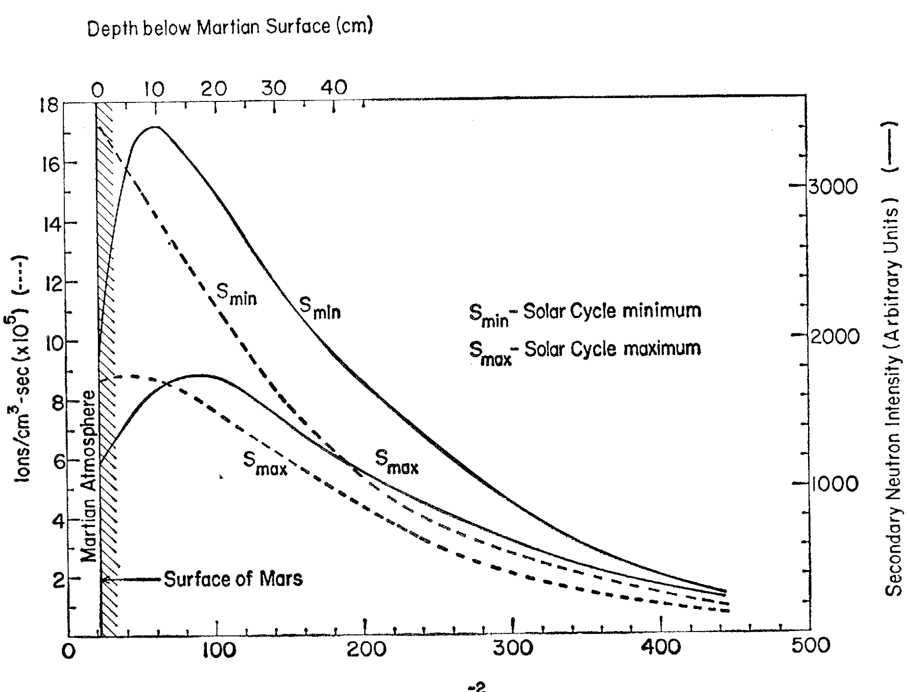


Fig. 10. Secondary production of ionization and fast neutrons from the integral primary cosmic-ray flux incident on the Martian atmosphere. The transition maximum is underground.

curves are similar to other interplanetary distributions studied in earlier months. We conclude with 99-percent confidence that no increase in counting rate greater than or equal to 1 count/sec was observed which could be associated with Mars. In view of the expected counting rates for a signature arising from a magnetospheric particle flux discussed above we conclude that the absence of this signature alone establishes an upper limit of $\mu \leq 2 \times 10^{-3}$.

A similar investigation of the $D_1D_2\bar{D}_3$ counting rate and the pulse-height distribution of analyzed events also revealed no additional particles associated with the planet.

Turning our attention to the transition region, we recall that multiple electron spikes are expected, similar to the case at Earth in Fig. 5 for $R > 13R_E$. For small values of μ, the shock and transition regions would be entered by Mariner IV towards the "evening side." It has been found (*15*) that there are fewer electron spikes in the transition region on the evening side than on the dawn side. There is approximately a 20-percent probability of seeing a single electron spike; if there are about ten of them, a substantial increase of intensity should have been observed with a probability of about 90 percent. No increase was observed.

Finally, if a bow shock existed, due to the presence of a magnetosphere, electron spikes will be found frequently beyond the shock (*3*). For this case the probability of our observing particles is about 50 percent. No radiation was detected.

From the above discussion we find that the upper limit of μ may be further reduced to $\mu \leq 10^{-3}$. Since the location of a magnetospheric boundary is not strongly dependent on the orientation of $\mathbf{M}_M$, we believe this result applies to almost all orientations of $\mathbf{M}_M$.

Mariner IV passed outside of, but near, any planetary wake which might have existed. However, if such a wake existed, particles might escape to the nearby planetary medium. We observed no evidence of additional particles.

We have searched and found no evidence for charged-particle radiation associated with Mars. In view of the close approach of the Mariner IV trajectory to Mars, we are able to set an upper limit to its magnetic moment provided we assume 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. We find that the magnetic moment of Mars is less than 10^{-3} that of Earth for a wide range of postulated orientations with respect to the rotation axis of Mars.

These conclusions lead to several implications bearing on the probable physical and biological conditions on the planet, some of which are:

1) The full intensity of cosmic radiation and solar flare protons in the vicinity of Mars will reach the top of the Martian atmosphere over the entire planet. Since observations by Mariner IV have shown (*5*) that this atmosphere is only about 10 g/cm^2, virtually the entire secondary production of particles from high-energy interactions takes place *below* the surface of Mars instead of in the atmosphere as at Earth. In Fig. 10 we have estimated the distribution of ionization (left-hand ordinate) and fast neutrons (right-hand ordinate) from the cosmic radiation using data obtained from measurements at Earth (*16*) and assuming that the surface density of the planet is its mean density, 3.97 g/cm^3. Solar-flare protons in excess of 100-Mev energy will also penetrate to the surface. It is important to note that a large fraction of the energy from cosmic ray interactions goes into π-meson production. Since these π-mesons are produced in the solid planet they will interact with nuclei below the Martian surface, instead of decaying to μ-mesons as they would in Earth's atmosphere. Consequently, secondary neutron and proton production in the solid planet considerably exceeds the production found at Earth. Thus, the production of radioactive and stable isotopes will be concentrated under the Martian surface. Since the density of Moon is 3.34 g/cm^3 we might expect that the secondary neutron flux escaping from Mars and Moon would be comparable.

2) It may be argued that a negligible magnetic moment for Mars means that it has no liquid iron-nickel core within which circulating current systems could be established. This may be correct, but it is not certain, since there are a variety of ways—suggested by studies of paleomagnetism—in which the internal motions may be slow and changing in character. However, the interior planetary conditions are not likely to be similar to Earth's.

3) If, in fact, a general Martian magnetic field is nonexistent the solar-wind protons are continually interacting with the Martian atmosphere. It is not yet clear from the competing effects of capture processes and escape of molecules through collisions whether or not the atmosphere has a lifetime comparable to the age of the planet. Perhaps Mars will have a "tail" of streaming molecules and ions whose origin is the Martian atmosphere.

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References and Notes

1. E. J. Smith, L. Davis, Jr., P. J. Coleman, Jr., D. E. Jones, *Science*, this issue.
2. N. F. Ness, C. S. Scearce, J. B. Seek, *J. Geophys. Res.* **69**, 3531 (1964), and references therein.
3. C. Y. Fan, G. Gloeckler, J. A. Simpson, *Phys. Rev. Letters* **13**, 149 (1964).
4. L. A. Frank, J. A. Van Allen and E. Macagno, *J. Geophys. Res.* **68**, 3043 (1963).
5. A. J. Kliore, D. L. Cain, G. S. Levy, V. R. Eshelman, F. Drake, *Science*, this issue.
6. R. Arnoult, *Ann. Phys. Ser. 11* **12**, 241 (1939).
7. C. Y. Fan, G. Gloeckler, J. A. Simpson, preprint, Enrico Fermi Institute for Nuclear Studies, 65-66, in press.
8. C. E. McIlwain, *J. Geophys. Res.* **66**, 3681, 1961.
9. Since the time for radio signals to travel from the spacecraft to Earth is 12 minutes, spacecraft time and Universal Time differ by approximately 12 minutes.
10. H. R. Anderson, J.P.L. interoffice memorandum, 3 May 1965.
11. G. D. Mead and D. B. Beard, *J. Geophys. Res.* **69**, 1169 (1964).
12. R. Blum, *Phys. Fluids*, in press.
13. Nat. Bur. Std. Central Radio Propagation Laboratory, Boulder, Colo., Rept. Ser. B, July 1965.
14. L. A. Frank, *J. Geophys. Res.* **70**, 1593 (1965), and references therein.
15. M. D. Montgomery, S. Singer, J. P. Conner, E. E. Stogsdill, *Phys. Rev. Letters* **14**, 209, 1965.
16. H. V. Neher, *Semaine d'Etude sur le Probleme du Rayonnement Cosmique dans l'Espace Interplanetaire* (Vatican City, Rome, 1963), p. 281; J. A. Simpson, in *Science in Space*, L. Berkner and H. Odishaw, Eds. (McGraw-Hill, New York, 1961), p. 266.
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