ANISOTROPIC PROPAGATION OF SOLAR PROTONS DEDUCED FROM SIMULTANEOUS OBSERVATIONS BY EARTH SATELLITES AND THE MARINER-IV SPACE PROBE*†

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It has been established recently by Ness and Wilcox[1] that solar magnetic fields carried into the interplanetary medium by the solar wind corotate with the sun and form a sectorlike structure[2] extending as a spiral past the orbit of Earth. Protons with energies ≥1 MeV persist for at least six solar rotations within some of these sectors.[3,4] It was shown that these protons did not originate in observable solar flares,[3] and their origin is still an open question. On the other hand, even the propagation of solar-flare protons in these interplanetary magnetic field structures is only partially understood.[5] For example, what role do magnetic field sectors and their corotation with the sun play in solar-flare particle propagation? To investigate this question it is necessary to study the spatial and time dependence of proton fluxes by making simultaneous particle measurements widely separated in space. These conditions were fulfilled by our concurrent charged-particle measurements on the Mariner-IV space probe and the IMP satellites at Earth. We observed both protons from solar flares and protons in the recurring 27-day sectors over a range of heliocentric longitudes of 104° and out to distances in excess of 1.5 astronomical units (A.U.).

The purpose of this note is to present experimental evidence that (a) some solar-flare protons are strongly confined to propagate in magnetic field regions which have the same characteristics as corotating sector structures and that these proton fluxes share this corotation; (b) the anisotropic propagation is so dominated by the prevailing magnetic field structure that differences in heliocentric longitude less than 40° are decisive for whether or not solar-flare particles may reach Earth, or any given point in space; and (c) the protons continually observed as 27-day recurring events in earlier experiments[3] are confined to corotating regions extending beyond 1.5 A.U. for several solar rotations.

We emphasize that these results were obtained under the special interplanetary conditions associated with the minimum in the solar activity cycle and all effects observed during 1965 are of very small magnitude as compared with the IMP-I results in 1964.[2,3] For high levels of solar activity these phenomena frequently may be masked by shock waves from solar flares, and other solar or interplanetary effects.

We believe that these conclusions will explain the observations also on the Mariner-IV spacecraft of >0.5-MeV proton intensity increases reported recently by Krimigis and Van Allen,[6] and Krimigis, Van Allen, and Coleman.[7]

Figure 1(a) is a cross-section view of the particle-detector elements and absorbers on Mariner-IV which form a cosmic-ray telescope separating protons from helium nuclei over the energy range 1-170 MeV/nucleon. This instrument, including its electron response, has been described elsewhere.[8] The IMP-II (launched October 1964) and IMP-III (launched May 1965) satellites carried more complex telescopes which, however, included the same energy ranges as Mariner-IV.[9] The measurements reported in this note are derived from two counting-rate channels corresponding to protons with energies >1 and >15 MeV from both the Mariner-IV and IMP instruments.

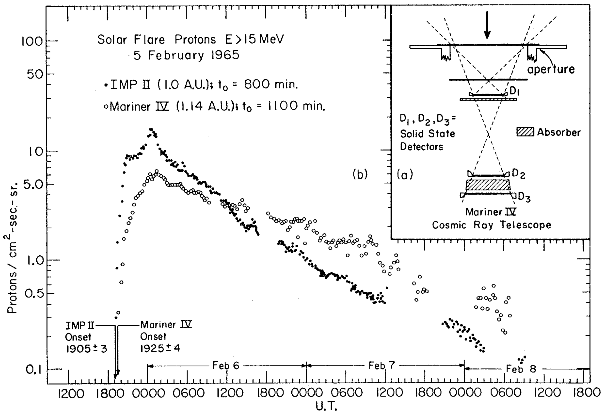

FIG. 1. (a) Cross section of Mariner-IV detector elements. Detectors D_1 and D_2 define a cone of acceptance of 40°. The telescope pointed directly away from the sun throughout the mission. (b) The decay time, t_0, for proton fluxes from the 5 February 1965 event was observed to be shorter at Earth than at Mariner-IV.

After Mariner-IV was launched on 28 November 1964, the first event of sufficient magnitude for analysis was the solar-flare proton event beginning 5 February 1965. We have already reported that the simultaneous observations by IMP-II and Mariner-IV showed that proton propagation for this event cannot be described by isotropic diffusion models,[10] even though the two spacecraft are quite close together (Mariner-IV was at 1.14 A.U. and almost directly in line with the sun and IMP-II as shown in Fig. 2). The intensities shown have been corrected for the respective background and geometrical factors of the two instruments. The errors in these corrections are <10%, whereas the observed differences are greater than a factor of 2 for more than 24 hours. The Mariner-IV telescope pointed directly away from the sun with an acceptance-cone angle of 40° so that particles traveling outward from the sun along the nominal direction for the magnetic field lines of 45-50° with respect to the radial direction will not enter the telescope. The IMP-II telescope was spinning so that it averaged over fluxes from all directions predominantly near the ecliptic plane. Hence, the observation by Mariner-IV of a proton intensity approximately a factor 2 above the intensity at IMP-II can only be explained by either (a) an anisotropic flux coming from the magnetic field direction leading toward the sun, or (b) a spatial variation of proton flux. This latter alternative is supported by independent evidence from other proton-intensity increases which we discuss later.

Spatial intensity variations arise from the interplanetary magnetic field which corotates with the sun. For example, superposed on the Mariner-IV trajectory in Fig. 2 is a family of Archimedes spiral lines representing idealized interplanetary magnetic field lines for a solar wind velocity of 400 km/sec.[11] For the 5 February flare the relative locations of the earth, Mariner-IV, and the flare on the sun are such that corotation past the spacecraft of a magnetic region, containing enhanced proton flux and following the general spiral pattern of the interplanetary magnetic fields,[12] may account for the observations in Fig. 1(b). That is, at early times the magnetic region connecting with the active region on the sun is closer to IMP while two days later it is closer to Mariner-IV. Thus, a higher intensity should be observed at early times at IMP and at later times at Mariner as shown in Fig. 1(b).

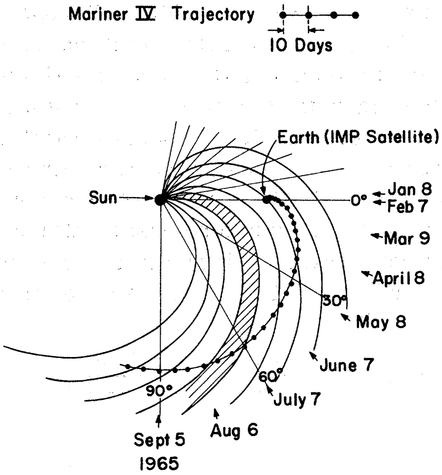

FIG. 2. The Mariner-IV trajectory with respect to the Earth-Sun system. The spiral lines, representing the idealized interplanetary magnetic field configuration, are separated by an amount equivalent to one day of solar rotation.

To proceed with the direct search for a possible corotation effect, we note the following factors dominating the propagation of low-energy protons. Following a solar flare, low-energy protons will leak from the intense magnetic field regions of the sun onto lines of force extending into the interplanetary medium. Small-scale magnetic structures or "channels" of enhanced field intensity within the large sector structure are assumed to provide the main channels for particle flow outward from the sun. Therefore, at any given time, we define the variation of the proton intensity over the longitudinal cross section of the magnetic channel as the proton intensity profile across this channel. The intensity and shape of the profile with time is determined primarily by (a) the rate of escape of protons from the sun, and (b) the degree to which particles are stored within the enhanced interplanetary magnetic field channel. Since both factors play significant roles in each solar-flare event, it is essential to measure proton intensity at two or more points in space separated spatially so that the effects of corotation are observable, yet spaced closely enough in time so that the proton profiles have not drastically changed between the times of the two measurements.

In Fig. 3 we have plotted intensity-time profiles for the data obtained on Mariner-IV and IMP-III from May 1965 until the end of data transmission on 1 October 1965. The data are arranged in successive solar rotations of 27 days as observed at Earth so that the times at which a magnetic structure—for example, the shaded region in Fig. 2—passes Earth in each rotation are given by a vertical line such as curve (a) in Fig. 3. The corresponding times at which the same structure passes Mariner-IV in its retrograde orbit relative to Earth are given by curve (b). Note that the time interval for corotation increases from approximately one day to about 6 days in this period.

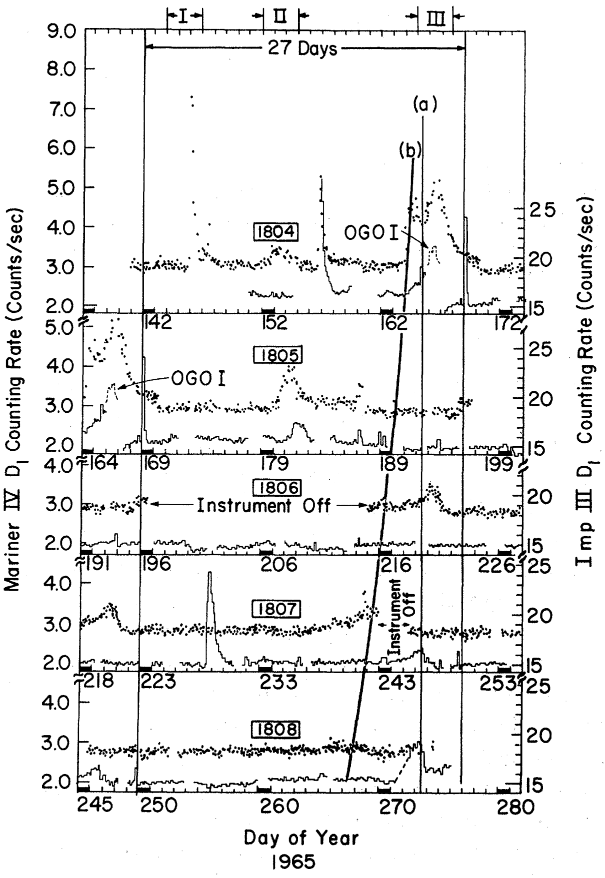

FIG. 3. The counting rates of the D_1 detectors on the Mariner-IV and IMP-III telescopes, each with a threshold for proton detection of 1 MeV, is shown for 5 successive 27-day periods. These periods correspond to the standard solar rotations numbered 1804 through 1808. The Roman numerals I, II, and III at the top of the figure give the range of onset times at which "27-day" recurring modulation of galactic cosmic radiation was detected by the Climax neutron-intensity monitor. The dots represent the Mariner-IV counting rate and the light solid line the IMP-III data. The gaps in the IMP-III data correspond to times when the satellite was passing through the earth's magnetosphere. Some fragments of OGO-I satellite data have been inserted to extend the data coverage at Earth.

All intensity profiles are for 1-MeV protons (or >200-keV electrons for solar-flare events on days 145 and 156[13]), and include both solar-flare-produced protons and 27-day recurring proton fluxes discussed in our introductory remarks. Based upon the fact that the intensity for protons >15 MeV (D_1D_2 events) did not increase during these small events, we conclude that the spectra for all these excess proton fluxes have negative slopes. This is known to be a characteristic of these two kinds of proton fluxes.[3]

Clearly it is important to search for proton intensity increases which are of solar-flare origin. To assist in this identification these events are listed in Table I along with the solar-flare data so far available. In this note we confine our attention to the most outstanding examples.

We shall consider three cases:

Case 1. Solar-flare proton propagation to one spacecraft but not the second spacecraft. The best example is the proton event on day 228 (Fig. 3; Table I). Protons from a large solar flare ~75° west of the sun-IMP-III line readily propagated to IMP-III. However, Mariner-IV, located with respect to the interplanetary field structure approximately 40° east of IMP-III, detected no increase of intensity. This example of the east-west solar-flare particle effect demonstrates the strong anisotropic propagation of solar protons in the interplanetary magnetic fields. Another example of this kind which is less certain, because there is no positive optical flare identification, begins on day 219. A proton flux reached Mariner-IV but was not detected at IMP-III.

Case 2. Solar-flare proton propagation with corotation of the interplanetary magnetic fields. The proton intensity increase beginning on day 180 at Mariner-IV was preceded by an importance-2 solar flare 36° east of the sun-earth line 26 hours earlier. It was not detected by IMP-III until approximately 0.7 day later (see Fig. 3; Table II). The difference between the calculated corotation time of 1.9 days and the measured corotation time of 0.7 day (measured between the times of first detection or peak intensity) may be due to lateral diffusion. A second event on day 164 may be of solar-flare origin, but this is not certain.

Case 3. 27-day recurring proton fluxes con-

Table I. List of low-energy particle-intensity increases observed on Mariner-IV and IMP-II and IMP-III.

Day of year (1965) of beginning of increase	Period of increase at Mariner-IV	Period of increase at earth satellite	Association with solar flares	Solar Modulation region[a]
9	8 January, 2000[b]–13 January, 0400	8 January, >1000–11 January, 0000	No association found	I
36	5 February, 1847–12 February, 0200	5 February, 1840– 9 February	Importance 2^+ flare, 5 February, 1750, N 8°, W 25°	I
145	25 May, 2350–28 May, 0400	No available observations	X-ray burst 25 May, 2241, N 19°, W 69°	I
152	1 June, 0200–4 June, 1000	Not detected	No association found	II
156	5 June, 2000–9 June, 1000	5 June, 2000–7 June, 0800	X-ray burst and type IV, 5 June, 1825, S 12°, W 50°	c
164	13 June, 0400–Indeterminate	13 June, 0800–Indeterminate	Imp. 2^+ flare, 9 June, 0600, N 22°, E 45°	III
166	15 June, 1000–19 June, 1000	15 and 16 June	Imp. 2 flare, 15 June, 0735, N 22°, W 30°	III
169	Not detected	17 June, 2100–18 June, 0400	No association found	c
180	29 June, 1200–2 July, 1800	30 June, 0600–1 July, 2000	Imp. 2^+ flare, 28 June, 1020, N 33°, E 36°	II
186	5 July, 2200–6 July, 2200	6 July, 0400–6 July, 0800	No association found	c
195	14 July, 1500–Indeterminate	Not detected	No association found	III
216	4 August, 0400–4 August, 2000	Not detected	No association found	III
219	7 August, 100°–11 August, 0200	Not detected	No association found	III
228	Not detected	16 August, 1400–18 August, 2000	Imp. 2 flare, 15 August, 0615, S 35°, W 75°	I
239	27 August, 0400–Indeterminate	1 September, 0000–4 September, 1200	No association found	III
265	22 September, 1000–26 September, 0400	27 September, 0020–30 September, 2300	No association found	III

[a] Based upon the analysis of the neutron monitor intensity at Climax, Colorado.[16] See Fig. 3.

[b] All times are universal time (UT).

[c] These events do not occur in any of the three recurring series.

Table II. Interplanetary magnetic field corotation times between Mariner-IV and Earth.

Solar modulation region relative to Earth	Solar rotation No.	Day of first detection by Mariner-IV	Predicted[a] corotation time (days)	Observed particle corotation time (peak to peak) (days)	Possible origin of protons
III	1804	164	1.0	0.4 ± 0.2	Flare
II	1805	180	1.9	0.7 ± 0.2, 0.6 ± 0.2[b]	Flare
III	1806	216	2.9	c	27 day
III	1807	239	4.0	4.7 ± 0.3, 4.5 ± 0.3[b]	27 day
III	1808	265	5.2	5.5 ± 0.4	27 day

[a] Assuming an average solar wind velocity $v_s = 400$ km/sec.

[b] Corotation time for secondary peaks within intensity-time profile.

[c] IMP-III passed into magnetosphere.

tinually confined to propagate in a magnetic sector. There is positive evidence against specific solar-flare production for many of the remaining intensity increases. On the other hand, these intensity increases fulfill the conditions required for 27-day recurring proton fluxes.[3] For example, the proton intensity increase beginning on day 239 at Mariner-IV was observed 4.7 days later at IMP-III with a predicted corotation time of four days as shown in Table II. Another example is the event observed at Mariner-IV on day 265 (Table II). From the data shown in Fig. 3, and from the discussion which follows, it appears that there is at least one 27-day recurring sequence of intensity increases.

Finally, there is convincing evidence for the presence of magnetic sector structures in the interplanetary medium at this time corresponding to these 27-day recurring proton-intensity profiles. It has been established that the 27-day recurring magnetic regions modulate the galactic cosmic-ray intensity,[14] producing a gradual depression of intensity each 27 days during the sweep of the magnetic region past Earth. We observed their correlation with corotating proton fluxes on the IMP-I satellite.[3] On the other hand, blast waves from solar flares produce sudden decreases in the cosmic-ray intensity (Forbush decreases) which are distinguishable from these 27-day recurring events.[15] From the modulation of cosmic-ray intensity observed in the Climax neutron-intensity monitor,[16] we find three recurring series of cosmic-ray intensity decreases due to modulation which begin on dates falling within the brackets labeled I, II, and III at the top of Fig. 3. All three regions, but especially region III which shows the best evidence for the recurring series, are dominated by the 27-day gradual modulation effect associated with corotating magnetic sectors.

The Mariner-IV magnetometer data so far available to us[17] show the characteristic field reversals expected on the basis of magnetic sector structure as deduced from the neutron-intensity monitor and the direct proton flux measurements.

The effect of corotating magnetic fields on the spatial distribution of solar proton intensity has been observed in the recent Pioneer-6 space probe and IMP-III measurements.[18]

Krimigis and Van Allen[6] and Krimigis, Van Allen, and Coleman[7] reported that they do not find strong evidence for 27-day recurring intensity increases. However, we believe that our analysis of these events, and the conclusions drawn from them, will explain their observations.

We are indebted to the staff of the Jet Propulsion Laboratory, especially H. Anderson and R. Holman, for integration of our experiment with the Mariner-IV spacecraft, and for preparations prior to launch. Within the Laboratory for Astrophysics and Space Research of our Institute, we wish to thank R. Jacquet, E. Grokulsky, and R. Takaki for engineering support, and H. Tibbs for assembly, calibration and checkout of the instruments. S. Myles, S. K. Roy, and R. Taft assisted in the preparation of computer programs and data analysis. We are indebted to P. Coleman for providing us with some preliminary information on the Mariner-IV magnetometer measurements.

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NEUTRON-PROTON ELASTIC SCATTERING FROM 1 TO 6 GeV*

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In this Letter we are reporting the first high-energy measurements (1- to 6.3-GeV kinetic energy) of neutron-proton elastic scattering extending from the small-angle, diffraction-peak region to the region beyond 90° in the center-of-mass system. Previous high-energy measurements[1,2] have concerned only elastic neutron-proton scattering near 180° in the so-called charge-exchange backward-peak region. This experiment was carried out at the Bevatron of the Lawrence Radiation Laboratory and used a neutron beam, spark chambers, and a liquid-hydrogen target. There were three objectives in this experiment: (1) to verify the existence of the expected but hitherto unobserved diffraction peak, to determine its parameters, and to investigate possible shrinkage; (2) to examine the differential cross section at and beyond 90° in the center-of-mass system, a region inaccessible in proton-proton scattering; (3) to look for the secondary forward peak which appears in pion-proton elastic scattering[3,4] but not in proton-proton elastic scattering.

The experiment involved a new technique using a neutron beam containing neutrons of all energies up to 6.3-GeV kinetic energy. Neutrons, produced by the external proton beam