Simultaneous Observations of Solar Protons Inside and Outside the Magnetosphere*

by

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April 1967

*Work supported in part by contract NAS5-9076 with Goddard Space Flight Center, by NsG 233-62 with the National Aeronautics and Space Administration, and by Nonr 1509(06) with the Office of Naval Research.

ABSTRACT

Simultaneous observations of low energy (~ 0.5 MeV) protons emitted in the solar flare of 7 July 1966 were made with University of Iowa detectors on board the earth satellites Explorer 33 and Injun IV, located outside and inside the earth's magnetosphere, respectively. We find that such protons have full and essentially immediate access from interplanetary space to the polar caps of the earth.

Early examples of simultaneous observations of solar cosmic rays with two widely separated spacecraft were in late March--early April 1960 with Explorer VII[1] and Pioneer V,[2,3] and in late September--early October 1961 with Injun I[4] and Explorer XII.[5] These measurements were made with somewhat dissimilar instruments whose energy thresholds were several MeV. O'Gallagher and Simpson[6] also reported simultaneous observations with the IMP-III earth satellite and the Mars-bound spacecraft Mariner IV, but the IMP-III satellite was outside the magnetosphere during the period of the reported observations. More recently, Krimigis and Van Allen[7] have reported simultaneous observations with Injun IV near the earth and Mariner IV (the latter located $\sim 23 \times 10^6$ km downstream from the earth and near the sun-earth line) and have concluded that the observed delay in arrival time for 0.5 MeV solar protons between the two spacecraft is 0 ± 2 hrs.

The present measurements make possible a much improved examination of the question of access of particles to the earth through the magnetosphere: (a) Explorer 33 is in the immediate astronomical vicinity of the earth, but clearly outside of the earth's magnetosphere (Figure 1); (b) the event of 7 July 1966 is of sufficiently high intensity that the statistical accuracy of the Injun IV counting rates is superior to those reported earlier by Krimigis and Van Allen[7] [see also Williams and Bostrom[8]]; and (c) the intensity-time structure is rich in detail, thus making possible a refined search for time delays. Because of (a) above, any dissimilarities in the intensity-time profiles between the two spacecraft can not be attributed to large scale ($\sim 10^6$ km) inhomogeneities in the interplanetary medium, as might have been the case for the Mariner IV and Injun IV comparison.

The University of Iowa detector complement on Explorer 33 consists, in part, of a 26.5 micron, totally depleted surface barrier silicon detector with discrimination levels set to count protons in the energy ranges $0.3 \leq E_p \leq 16$ MeV, $0.5 \leq E_p \leq 4.2$ MeV, and $0.82 \leq E_p \leq 2.0$ MeV. All channels are insensitive to galactic cosmic rays and to electrons of any energy in the intensities found to be present by the G-M tubes during the Explorer 33 flight. The detector is equipped with a weak $_{95}Am^{241}$ source of alpha particles to provide assurance of its proper operations in flight. The conical collimator of the detector has a half-angle of 30°, and the spacecraft is spinning at the rate of ~ 26 rpm. The detector counting rate is spin-averaged over 11 rotations during intervals spaced by 81.8 seconds. The absolute value of the unidirectional geometric factor is 0.082 ± 0.003 cm^2-sr. The University of Iowa detector on

Injun IV relevant to this study is a silicon detector virtually identical to that on Explorer 33, with energy levels set to count protons in the energy ranges $0.52 \leq E_p \leq 4.2$ MeV and $0.90 \leq E_p \leq 2.1$ MeV. The detector half angle is 20° and the unidirectional geometric factor is 0.0064 ± 0.0007 cm^2-sr. The Injun IV satellite is magnetically oriented so that the detector axis is continuously perpendicular to the direction of the local magnetic field. Simultaneous data from G-M tubes on both satellites assure that all protons reported herein are in fact entering the solid state detector through its collimator and not through the protective shield.

Figure 2 shows the counting rate vs time profile of the $0.5 \leq E_p \leq 4.2$ MeV channel from Explorer 33 (solid curve) and the counting rate vs time profile of the equivalent channel from Injun IV (plotted points) obtained while the latter satellite (orbital inclination 81°) was moving over the earth's polar caps at an altitude ranging from 1500 to 2000 km. The solid curve was drawn by using half-hour averages of the counting rate, while the plotted points represent 8-16 minute averages of the Injun IV counting rate over the polar caps. Since the unidirectional geometric factors of the two detectors differ by approximately a factor of 10 (within 25%), the Injun IV points were moved up one decade in the logarithmic scale so that the absolute values of the intensity at the positions of the two satellites can be compared directly. It is seen that

(a) The absolute intensities of protons in identical energy channels are essentially the same moment-by-moment (within the uncertainties in the geometric factors and the statistics) in interplanetary space and over the polar caps of the earth, during the entire 4-day period of simultaneous observations.

(b) There are statistically significant differences in only two or three instances (e.g., ~ 1800 UT, 9 July), which are attributed tentatively to marked anisotropies in the interplanetary intensity and/or to strong polar magnetic storms.

We therefore conclude that, on the whole, low energy (~ 0.5 MeV) solar protons have full access to the earth's polar caps from the interplanetary medium, with a delay of 0.5 hour or less.

Of particular interest is the abrupt decrease in the intensity at about 2300 UT on 8 July. A more detailed plot of this period shows that while the counting rate at the position of Explorer 33 is still decreasing, the rate at Injun IV has already decreased to the new level. We infer from this observation that the decrease in intensity at Injun IV preceded that at Explorer 33 by at least 8 minutes. Van Allen and Ness[9] have reported that during 7-8 July the bulk-velocity of the propagation of plasma clouds is 950 km/sec. In view of this result, and the knowledge of the relative positions of the two satellites, one would expect that any increases and/or decreases in the intensity at Injun IV should be followed in about 4 minutes by similar increases and/or decreases at Explorer 33. Thus the observed decrease of the intensity at Injun IV followed by the decrease at Explorer 33 is in crude agreement with a picture of a plasma cloud moving radially outward from the sun past the earth and past Explorer 33, in that order, carrying the energetic particles with it.

Although it has been established that the magnetospheric boundary is greatly distorted by the flow of the solar wind, there is essential disagreement regarding the details of the magnetic field topology at the boundary between the magnetosphere and the interplanetary medium. Figure 3 shows two of the proposed magnetospheric models. The model shown in 3a envisions considerable merging between the geomagnetic and interplanetary magnetic fields (cf. Dungey, 1961; Levy et al., 1964),[10,11,12] such that a particle moving on an interplanetary magnetic field line would have immediate access to any point over the earth's polar caps.

The model shown in Figure 3b envisions no merging between the geomagnetic and interplanetary fields (cf. Dessler, 1964).[13]

Proponents of this model theorize that low energy protons ($E_p \lesssim 5$ MeV) must diffuse into the tail of the magnetosphere and spread slowly from the auroral zone over the polar caps after a delay or "diffusion time" which is a function of, among other parameters, the length of the tail and the energy/unit charge of the particle.[14] Thus, for a 0.5 MeV proton, the delay in onset time between a detector located outside the magnetosphere and an identical detector located over the earth's polar caps is found to be about 30 hours, assuming that the length of the tail is 1 A.U. [see eq. 4 of Michel and Dessler, where E_q is energy/charge (Dessler, private communication)]. It is seen from Fig. 1 that Explorer 33 was located clearly outside the shock front [data on shock front location courtesy of K. W. Behannon and N. F. Ness].

Thus, our observations are in drastic disagreement (Fig. 2) with the magnetospheric tail model of Michel and Dessler.[14] Possible explanations for the above observations are:

(a) That the length of the tail is so small (i.e., less than or of the order of 1000 earth radii) that the diffusion time for 0.5 MeV protons is less than 0.5 hour (Michel and Dessler model) (It is noted that Michel and Dessler[14] state that for diffusion into the tail to be effective, the tail must be longer than about 1 A.U.); <u>or</u>

(b) That the tail length is not a relevant parameter, but that there exists effective merging between the geomagnetic and interplanetary magnetic fields (Dungey and Levy et al. model).

Hence, we favor explanation (b) as a more plausible alternative.

It should be recognized that the above discussion has been based on the concept of a single particle moving in a quasi-stationary magnetic field, and that collective (plasma) phenomena have been ignored. Transport of a fully ionized plasma across a magnetic field at a rate much faster than that attributable to single particle diffusion has been observed in the laboratory. This phenomenon of anomalous diffusion was first investigated by Spitzer[15] and more recently by Stix,[16] and shown to be due to the presence of electric fields. Thus, it may be that interconnection between the lines of force of the interplanetary and geomagnetic fields is not necessary for access of low energy protons to the earth's polar caps, if they are only a minor component of a much more dense plasma cloud. Thus, theoretical discussions on the subject of interconnection of lines of force may be irrelevant to this matter.

The authors thank Dr. D. C. Montgomery for informative discussions on the subject of anomalous diffusion.

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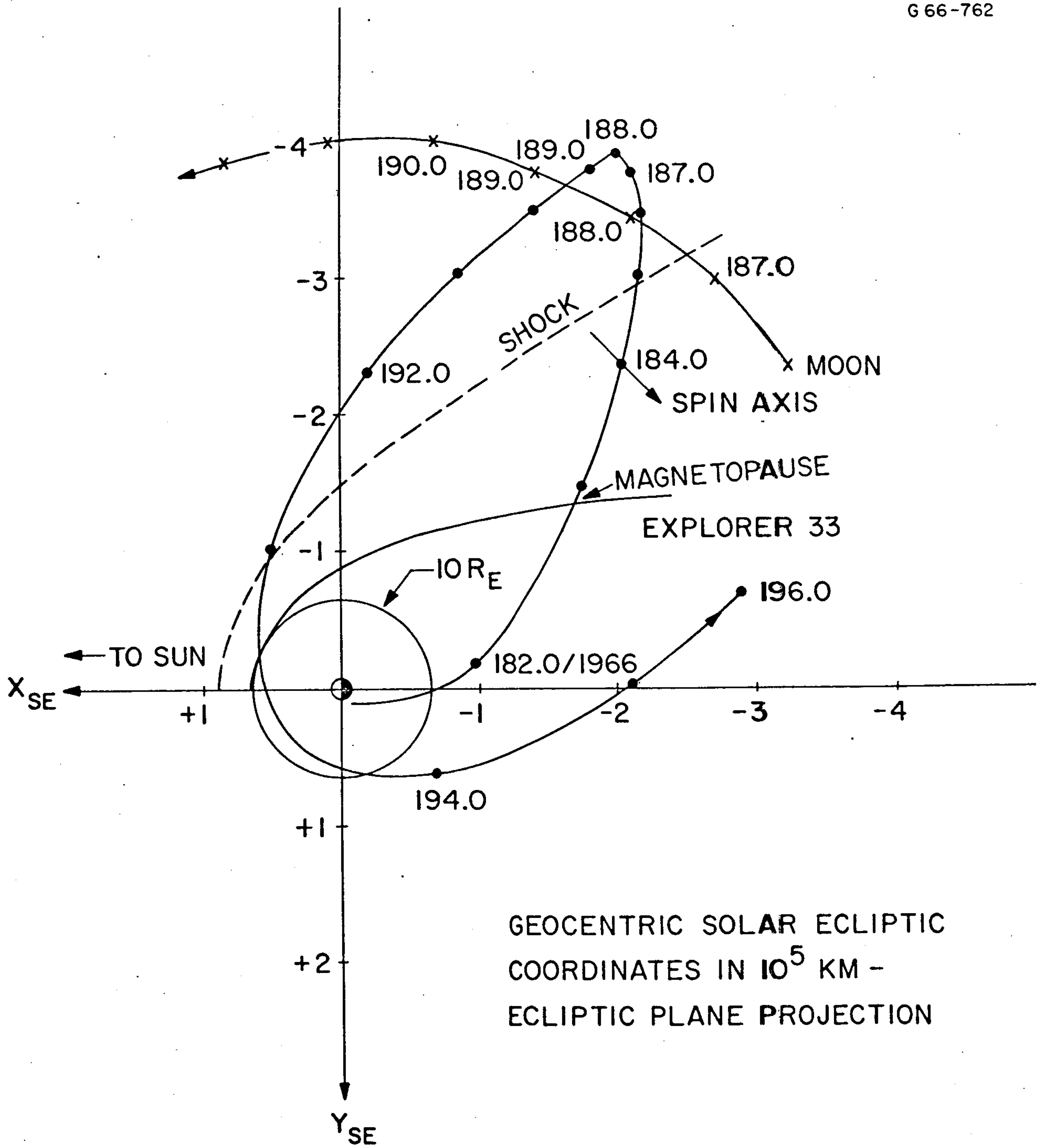
FIGURE CAPTIONS

Figure 1. Ecliptic plane projection of the first orbit of Explorer 33 and a segment of the orbit of the moon, both in geocentric solar ecliptic coordinates. Note that during the period of observations, Explorer 33 was on the sunward side of the shock front [shock front and magnetopause locations courtesy of K. W. Behannon and N. F. Ness].

Figure 2. Simultaneous observations of directional intensities of solar protons with Explorer 33 and Injun IV. The smooth curve is drawn through half-hour averaged counting rates of Explorer 33. Each plotted point represents a polar cap averaged counting rate for Injun IV. The respective sets of data are superimposed on the same absolute intensity basis (to within 25%) by displacing the counting-rate scale of Injun IV data upward by one decade.

Figure 3. (a) Magnetospheric model that envisions merging between the geomagnetic and interplanetary fields.[10,11]

(b) Magnetospheric model in which merging of lines of force does not occur.[13,14]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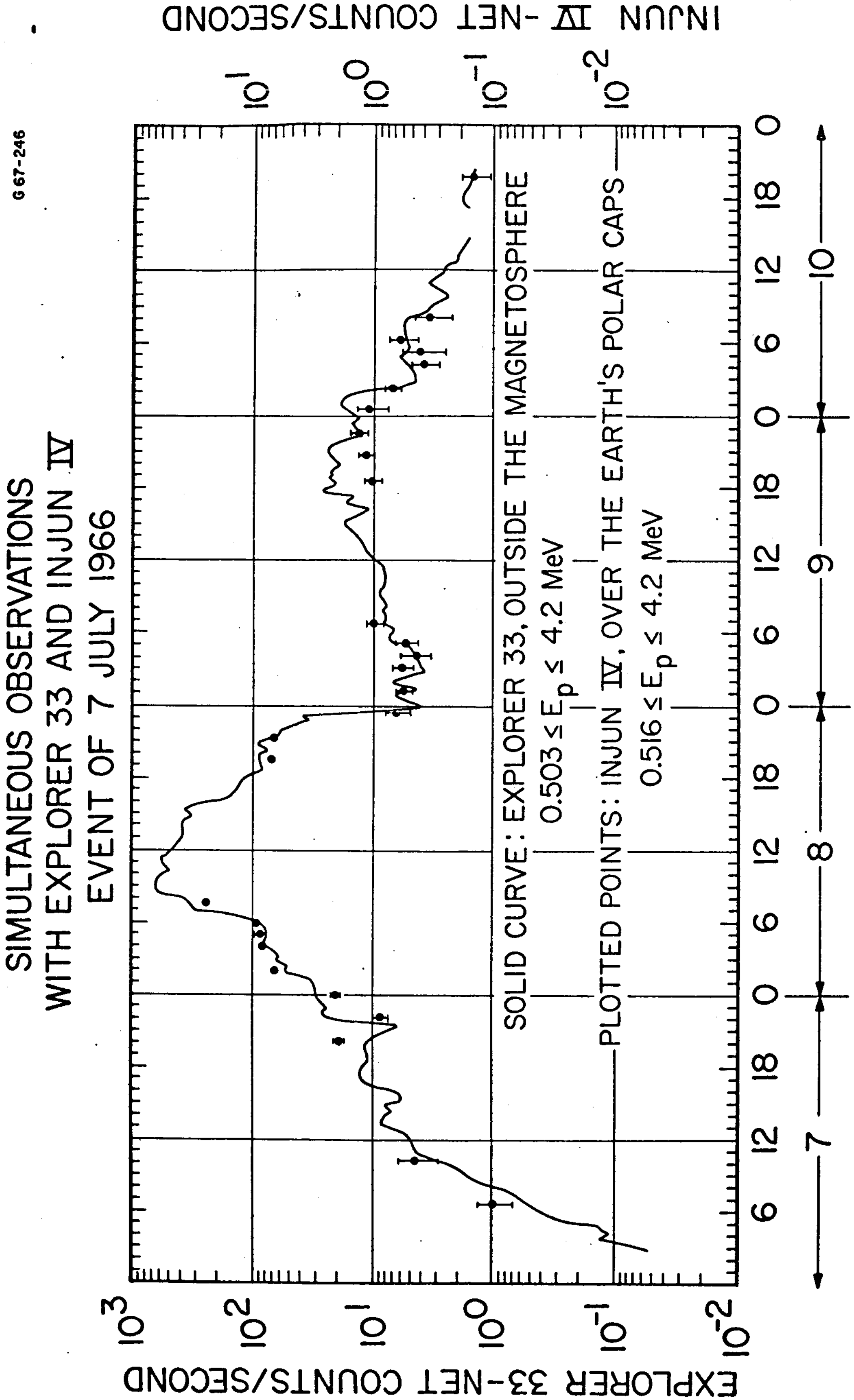
COORDINATES IN 10^5 KM -
ECLIPTIC PLANE PROJECTION

Figure 1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SIMULTANEOUS OBSERVATIONS
WITH EXPLORER 33 AND INJUN IV
EVENT OF 7 JULY 1966
SOLID CURVE: EXPLORER 33, OUTSIDE THE MAGNETOSPHERE
0.503 ≤ E_p ≤ 4.2 MeV
PLOTTED POINTS: INJUN IV, OVER THE EARTH'S POLAR CAPS
0.516 ≤ E_p ≤ 4.2 MeV
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INJUN IV-NET COUNTS/SECOND
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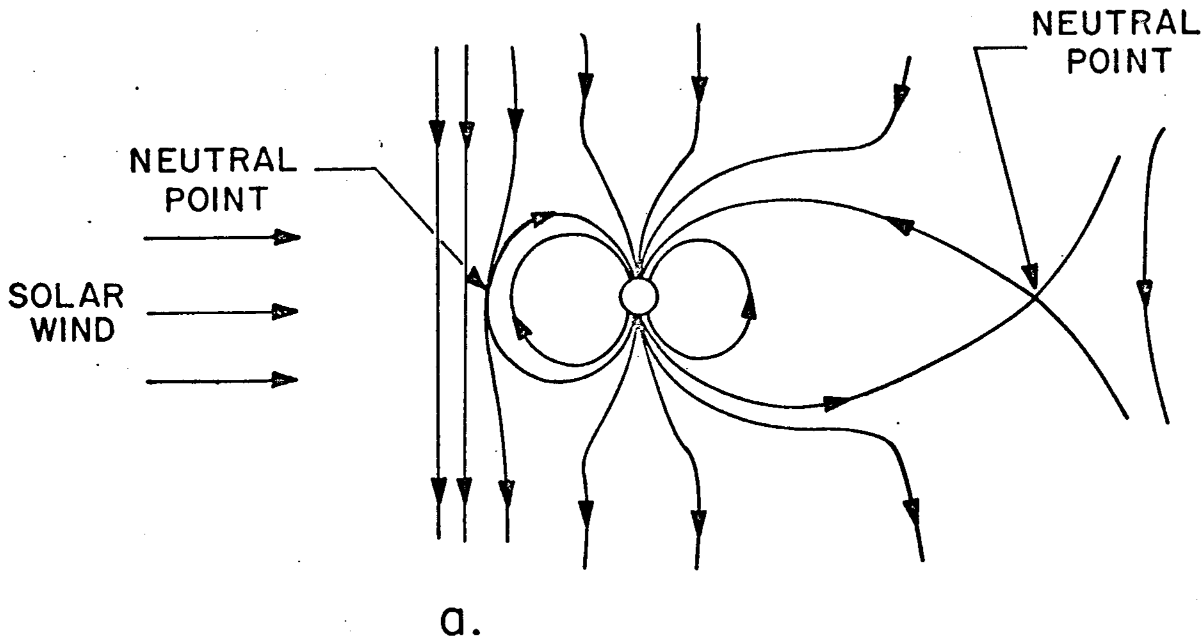
Figure 2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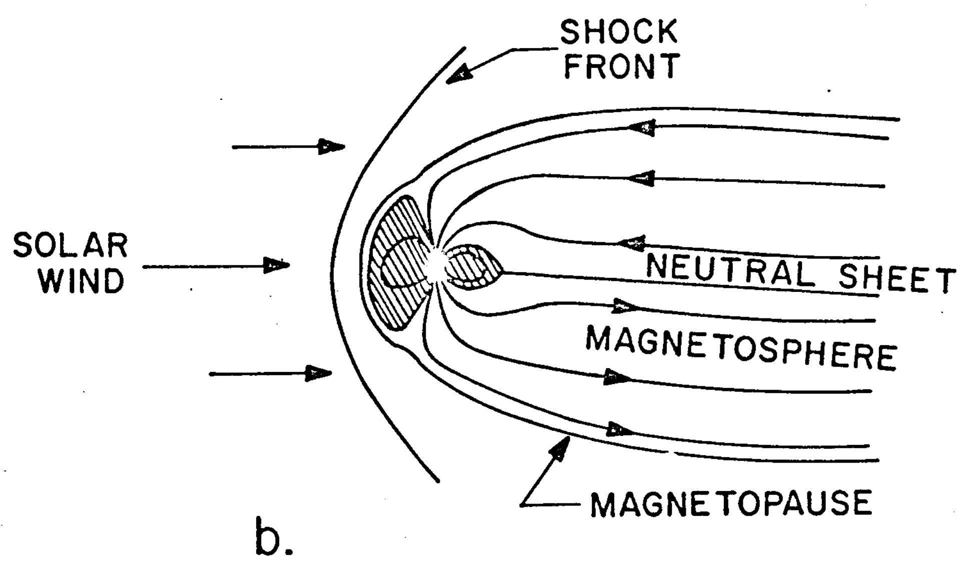
SHOCK FRONT
SOLAR WIND
NEUTRAL SHEET
MAGNETOSPHERE
MAGNETOPAUSE
b.

Figure 3

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1. ORIGINATING ACTIVITY *(Corporate author)* University of Iowa Department of Physics and Astronomy		2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	
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3. REPORT TITLE Simultaneous Observations of Solar Protons Inside and Outside the Magnetosphere			
4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)* Progress April 1967			
5. AUTHOR(S) *(Last name, first name, initial)* Krimigis, S. M., Van Allen, J. A., and Armstrong, T. P.			
6. REPORT DATE April 1967		7a. TOTAL NO. OF PAGES 15	7b. NO. OF REFS 16
8a. CONTRACT OR GRANT NO. Nonr 1509(06)		9a. ORIGINATOR'S REPORT NUMBER(S) U. of Iowa 67-13	
b. PROJECT NO.			
c.		9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*	
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