JOURNAL OF GEOPHYSICAL RESEARCH, SPACE PHYSICS VOL. 74, NO. 21, OCTOBER 1, 1969

Brief Reports

Access of Solar Protons into the Polar Cap: A Persistent North-South Asymmetry

L. C. EVANS AND E. C. STONE

California Institute of Technology
Pasadena, California 91109

Before the magnetic storm sudden commencement during the November 2, 1967, solar particle event, the access of 1.2- to 40-Mev protons into the high-latitude portion of the northern polar region was delayed by ~20 hours. At the same time the access delay for 10- to 40-Mev protons was $\lesssim 1$ hour in the southern polar region and at middle northern latitudes. The implications of the north-south asymmetry are discussed.

The rate of access of low-energy protons into the polar regions can be sensitive indicator of possible merging of the interplanetary and geomagnetic fields [*Dungey,* 1961; *Axford et al.,* 1965; *Michel and Dessler,* 1965]. Generally, direct (prompt) access of solar protons is expected to occur on geomagnetic field lines that have merged with the interplanetary field lines. Access delay times of $\lesssim 0.5$ hour during the July 7, 1966, event were reported as evidence of merging at that time [*Krimigis, et al.,* 1967].

Similarly, the access delay at the onset of the February 5, 1965, event was consistent with significant field line merging, although statistically significant differences between the interplanetary and polar proton fluxes were observed [*Krimigis and Van Allen,* 1967; *Williams and Bostrom,* 1967]. There were also indications that significantly different intensities occurred in the northern and southern polar regions [*Krimigis and Van Allen,* 1967; *Reid and Sauer,* 1967]. After the sudden commencement, the delay time was 3 to 5 hours, which is suggestive either of direct access into the magnetotail 0.4 AU from the earth, or of diffusion effects in an unmerged magnetotail [*Williams and Bostrom,* 1967].

Latitude-intensity structure in both polar regions during the post-sc period of the August 28, 1966, event was in qualitative agreement with diffusion, although the access delay was no greater than 1 hour [*Blake et al.,* 1968]. Similarly, access delays of 1.5–5 hours during a magnetically disturbed period on May 26, 1967, are in qualitative agreement with diffusion [*Williams and Bostrom,* 1969].

The minimum access time observed in the magnetotail at 19 R_E for a series of other events was ~15 minutes, with occasional delays of 1–3 hours. Most of the observations were consistent with diffusion, although some required merging within 2000 R_E [*Montgomery and Singer,* 1969].

The present observation is quantitatively different from those above in that the access delay was in excess of 20 hours near the center of the northern polar region; at the same time it was $\lesssim 1$ hour at lower northern latitudes and in the southern polar region. During the 20 hours, the interplanetary proton flux was essentially isotropic (J. Sullivan and J. A. Simpson, personal communication, 1969), and the geomagnetic field was relatively quiet.

These results were obtained from a joint University of Chicago/California Institute of Technology experiment on OGO 4. The instrument, which was launched into a low-altitude polar orbit, contains two cosmic-ray detector systems. The primary detector system is a sandwich of absorbers and two circular surface barrier solid-state detectors (D1 and D2) inside a plastic scintillator anticoincidence cup (D3), which defines a vertical acceptance cone with a 30° half-angle, resulting in a geometrical factor of ~1.1 cm² ster. Both detectors have nominal 240-μm depletion depths and are covered by a 2.6-mg/cm² aluminized mylar window. The

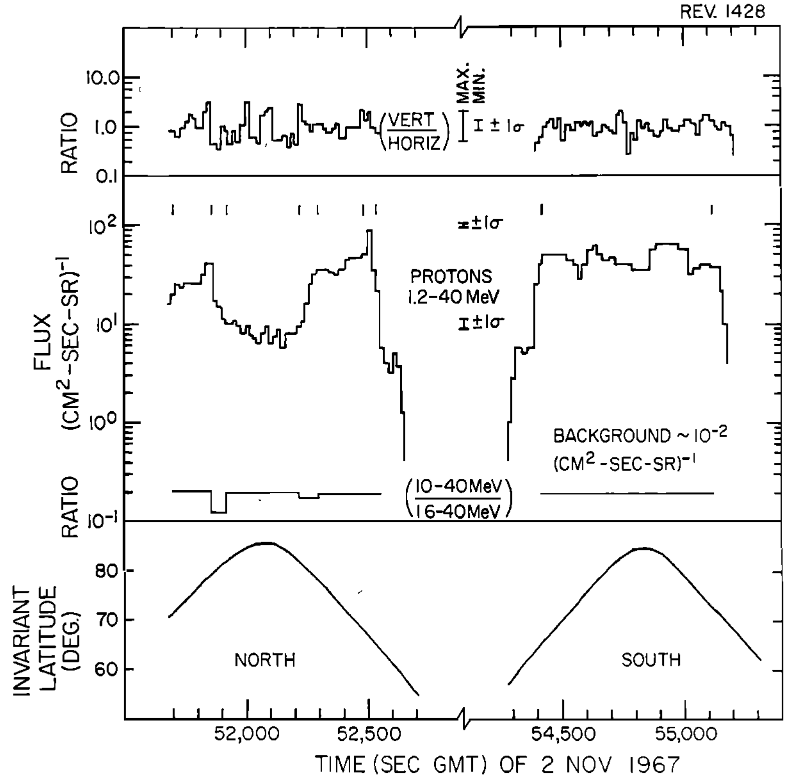

Fig. 1. Selected north and south polar passes early during the event of November 2, 1967, showing the details of the observed north-south asymmetry. Isotropy is indicated by a vertical/horizontal ratio of unity. Any spectral change would be indicated by a change in the 10–40 Mev/1.6-40 Mev proton ratio, which has a statistical error of $\lesssim 1\%$. Invariant latitude is included for reference. The time of these polar passes (rev. 1428) is indicated in Figure 2.

energy loss in the front detector (D1) is pulse-height-analyzed for protons ($1.2 \leq E_p \leq 39$ Mev), α particles ($4.4 \leq E_\alpha \leq 156$ Mev), and electrons ($0.4 \leq E_e \leq 1$ Mev). Response of the rear detector (D2) indicates a more energetic event, i.e., $9.2 \leq E_p \leq 39$ Mev, $37 \leq E_\alpha \leq 156$ Mev, or $0.7 \leq E_e \leq 1$ Mev. The counting rates D1$\overline{\text{D3}}$, D2$\overline{\text{D3}}$, D1D2$\overline{\text{D3}}$, and D3 are also monitored.

The secondary detector system is a 0.08-cm^2 surface barrier detector with a nominal 25-μm depletion depth, covered by a 1.2-mg/cm^2 aluminized mylar window. A magnesium collimator defines a horizontal acceptance cone with a 22° half-angle, resulting in a geometrical factor of 0.016 cm^2 ster. Only the counting rate from this horizontal detector is monitored, corresponding to protons ($0.81 \leq E_p \leq 11$ Mev) and α particles ($2.76 \leq E_\alpha \leq 235$).

A 2B flare occurred on the sun at 0852 UT on November 2, 1967, accompanied by 2–12 A X-ray emission that peaked at 0858 UT. The particle intensity was reasonably uniform over the south polar region for all passes after 1200 UT. The 1.2- to 40-Mev proton intensity is shown in Figure 1 for a southern polar pass early in the event. Intensity profiles from later southern passes exhibit even less structure. In contrast, the proton intensity profiles in the northern polar region show a pronounced minimum at $\Lambda \gtrsim 72°–80°$ similar to that shown in Figure 1, although the maximum intensity between ~65° and ~80° was comparable to that in the southern region. The same ratio of minimum to maximum intensity occurred over the entire measured energy range from 1.2 to 40 Mev, as indicated both by the ratio of the intensity of 10- to 40-Mev protons to that of 1.6- to 40-Mev protons shown in Figure 1 and by pulse height analysis. Figure 1 also contains the ratio of the vertically incident to the horizontally incident flux, normalized so that unity corresponds to an isotropic flux. There is no evidence of a large anisotropy in conjunction with the intensity variations, ruling out a pitch-angle dependent cutoff effect.

The time variation of the 1.2- to 40-Mev proton flux is shown in Figure 2 for the southern polar region, for the region of maximum northern intensity, and for the region of minimum northern intensity for each available orbit. Both the southern and northern maximum fluxes increased rapidly, while the northern minimum intensity increased slowly over a period of ~20 hours. Although the northern minimum intensity monotonically increased, the ratio of

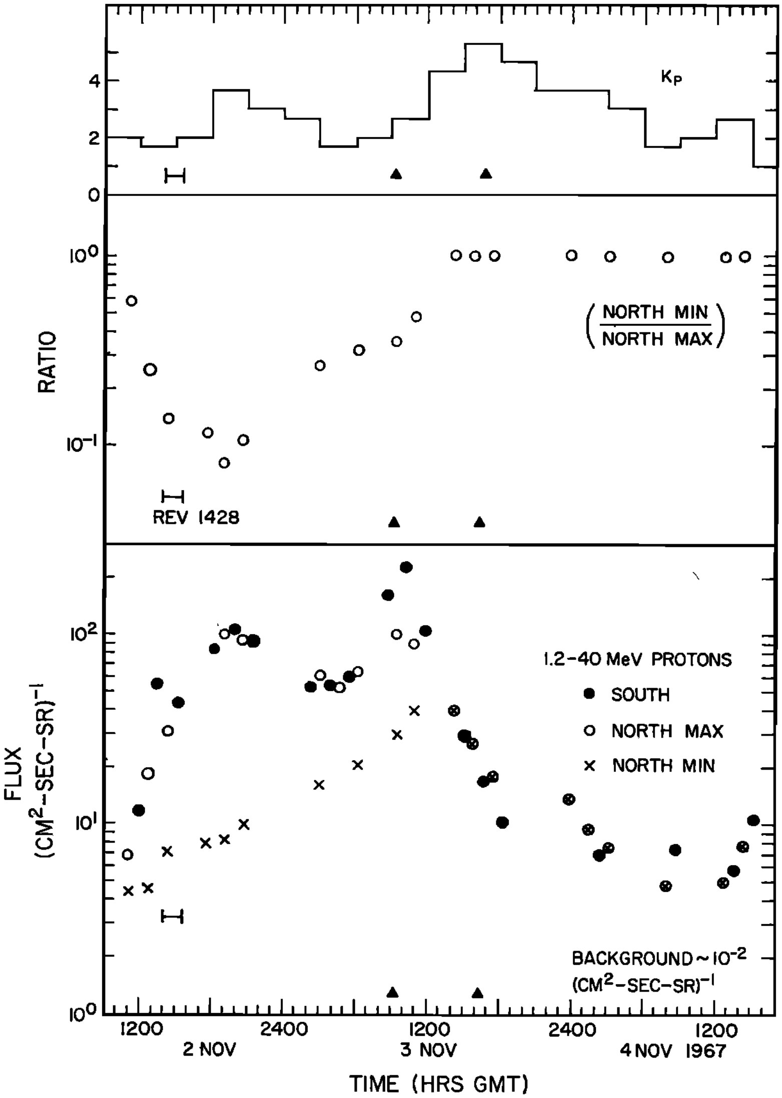

Fig. 2. Time variation of the observed north-south asymmetry in the 1.2–40 Mev proton flux. The delayed access of protons into the high latitudes of the north polar region is compared with the rapid access of protons into the south polar region and low latitudes of the north polar region. Systematic errors are $\lesssim 10\%$. The *Kp* index and sudden commencements (sc) are indicated for reference. A reversal in the interplanetary magnetic field occurred at ~1400 UT on November 3, 1967.

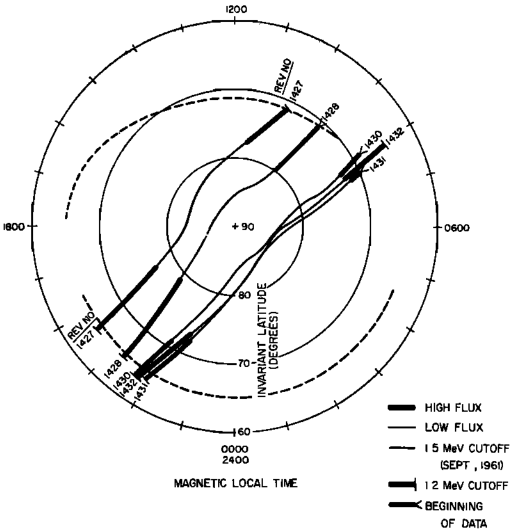

Fig. 3. A mapping of the north polar passes of OGO 4 into invariant latitude-magnetic local time coordinates showing the location of the regions of maximum and minimum proton fluxes. Observed geomagnetic cutoffs are indicated and compared with cutoffs reported for a quiet geomagnetic field in September 1961. Where cutoffs were not observed, the beginning of data acquisition is indicated.

minimum to maximum intensity reached a lowest value of $\lesssim 0.1$ approximately 9 hours after the flare.

By 1445 UT on November 3, 1967, the intensity had become uniform over the northern polar region, perhaps in association with the reversal of the direction of the interplanetary field from negative (solar directed) to positive (antisolar directed) at ~1400 UT [*Wilcox and Colburn,* 1969]. Before the two sudden commencements on November 3, 1967 (0914 UT and 1627 UT), the magnetic field was reasonably quiet as indicated by the Kp index plotted in Figure 2.

The mapping of the regions of maximum and minimum intensity into the invariant latitude-magnetic local time (Λ-MLT) coordinate system is shown in Figure 3, along with the low-latitude rigidity cutoff previously determined for 1.5-Mev protons during a magnetically quiet period in 1961 [*Stone,* 1964]. The proton intensity during the 1961 observation showed no evidence of a minimum in the center of either polar region. Thus, the two observations indicate a similar low-latitude behavior, i.e., the same cutoff latitude, even though the high-latitude behavior is markedly different.

Gall et al. [1968], in their investigation of the arrival of low-energy cosmic rays via the magnetospheric tail, have distinguished three latitude regions. In the high-latitude region the lines of force extend back into the magnetotail. In the magnetospheric model used by *Gall et al.* [1968], the high-latitude region extends down to 80° at local noon and 69° at local midnight. More recent analysis of magnetic field measurements indicates that in an average magnetosphere the corresponding latitudes are 78° ± 3° and 69° ± 2° [*Fairfield,* 1969]. The intermediate latitude region corresponds to distorted but closed lines of force and extends down to approximately 60°. The low-latitude region extends down to the equator, is normally unaffected by the magnetotail, and is generally inaccessible to low-energy protons ($\lesssim$500 Mev).

Re-examination of Figure 3 shows that the minimum intensities might be associated with the high-latitude region (open field lines), while the maximum intensities might be associated with the intermediate latitude region (closed, distorted field lines). As shown in Figure 2, the northern maximum intensities generally agree with the southern intensities, as expected for closed field lines. However, the intensities at high latitudes are not the same in the north and south, indicating that access to open field lines in the magnetotail is significantly different in these two regions and that access across the neutral sheet from the southern to the northern high latitude region is inhibited for protons with energies between 1.2 and 40 Mev.

These high-latitude observations are not consistent with any present model for proton access into the magnetosphere. In particular, merging of interplanetary and geomagnetic field lines at the front of the magnetosphere [*Axford et al.,* 1965; and *Dungey,* 1961] would result in symmetrical north-south field line connections and similar proton access times. A north-south asymmetry might result if, as suggested by *Reid and Sauer* [1967], field lines directly from the sun connect to only one polar cap. The sector direction was indeed appropriate for connection to the south during the 20-hour asymmetry, changing direction at approximately the same time as the asymmetry vanished. The time dependence of the 10-Mev south polar flux is, however, also consistent with that reported for the diffusion of solar protons into the magnetotail at 19 R_E. Preliminary comparisons of the south polar fluxes of 10-Mev protons with hourly averaged interplanetary fluxes [*Bostrom et al.*, 1968] indicate a delay of $\lesssim$1 hour. More detailed comparisons are required to distinguish between diffusion and direct access in the south polar region.

The delayed access of the proton flux in the northern high-latitude region probably results from the diffusion of solar protons into the magnetotail. The only model presently proposed for this process [*Michel*, 1965; and *Michel and Dessler*, 1965] necessarily involves a number of simplifying assumptions. The model is based on a cylindrical magnetotail long enough for protons to radially diffuse into the center of the tail in a time that is less than that required for longitudinal diffusion along the tail into the polar regions. The model requires that the gyroradius of the particle be smaller than the radius of the northern magnetotail, i.e., $E \lesssim$ 20 Mev for protons. For a tail length of 1 AU, a diffusion time of ~15 hours is predicted for 1-Mev protons, which is comparable to the observed delay time. However, the predicted diffusion time is not independent of energy, while the observed delay time seems to be. Also, it was predicted that diffusion would not be important for protons with $E \gtrsim$ 20 Mev, in contrast to the present observation.

A more detailed model of proton access would have to account for the following observations:

(1) Long delay times (~20 hours), without a strong energy dependence.
(2) Long delay times for protons with gyroradii comparable to the magnetotail radius.
(3) Faster access to one high-latitude polar region than to the other, possibly associated with the direction of the interplanetary field.
(4) Equally rapid access to both middle latitude polar regions.
(5) Restricted access from north to south across the neutral sheet.

Acknowledgments. We gratefully acknowledge the collaboration and support of Drs. J. A. Simpson and C. Y. Fan during various stages of this joint University of Chicago/California Institute of Technology program. The instrument was constructed by the Laboratory for Astrophysics and Space Research of the University of Chicago. We also thank Dr. L. Davis, Jr., for helpful discussions.

This work was supported by the National Aeronautics and Space Administration under contract NAS 5-3095 and grant NGL 05-002-007.

REFERENCES

Axford, W. I., H. E. Petschek, and G. L. Siscoe, Tail of the magnetosphere, *J. Geophys. Res., 70,* 1231, 1965.

Blake, J. B., G. A. Paulikas, and S. C. Freden, Latitude-intensity structure and pitch-angle distributions of low-energy solar cosmic rays at low altitude, *J. Geophys. Res., 73,* 4927, 1968.

Bostrom, C. O., D. J. Williams, and J. F. Arens, Solar protons by satellite-Explorer 34, *IER-FB Solar Geophysical Data,* 132, 1968.

Dungey, J. W., Interplanetary magnetic field and the auroral zones, *Phys. Rev. Letters, 6,* 47, 1961.

Fairfield, D. H., The magnetic field of the magnetosphere and tail, *GSFC preprint X-616-69-124,* 1969.

Gall, R., J. Jiménez, and L. Camacho, Arrival of low-energy cosmic rays via the magnetospheric tail, *J. Geophys. Res., 73,* 1593, 1968.

Krimigis, S. M., and J. A. Van Allen, Observations of the February 5–12, 1965, solar particle event with Mariner 4 and Injun 4, *J. Geophys. Res., 72,* 4471, 1967.

Krimigis, S. M., J. A. Van Allen, and T. P. Armstrong, Simultaneous observations of solar protons inside and outside the magnetosphere, *Phys. Rev. Letters, 18,* 1204, 1967.

Michel, F. C., Effect of the magnetospheric tail on cosmic ray cutoffs, *Planetary Space Sci., 13,* 753, 1965.

Michel, F. C., and A. J. Dessler, Physical significance of inhomogeneities in polar cap absorption events, *J. Geophys. Res., 70,* 4305, 1965.

Montgomery, M. D., and S. Singer, Penetration of solar energetic protons into the magnetotail, *J. Geophys. Res., 74,* 2869, 1969.

Reid, G. C., and H. H. Sauer, Evidence for nonuniformity of solar-proton precipitation over the polar caps, *J. Geophys. Res., 72,* 4383, 1967.

Stone, E. C., Local time dependence of non-Störmer cutoff for 1.5-Mev protons in quiet geomagnetic field, *J. Geophys. Res., 69,* 3577, 1964.

Wilcox, J. M., and D. S. Colburn, Interplanetary sector structure in the rising portion of the sunspot cycle, *J. Geophys. Res., 74,* 2388, 1969.

Williams, D. J., and C. O. Bostrom, Proton entry into the magnetosphere on May 26, 1967, *J. Geophys. Res., 74,* 3019, 1969.

Williams, D. J., and C. O. Bostrom, The February 5, 1965, solar proton event, 2, Low energy proton observations and their relation to the magnetosphere, *J. Geophys. Res., 72,* 4497, 1967.

(Received July 7, 1969.)