



SOLAR-TERRESTRIAL DISTURBANCES

The period from July 12 to 28, 1961, was extremely unusual and notable for the geophysicist by the appearance of a large number of solar flares followed by such geophysical phenomena as magnetic storms and ionospheric disturbances. During this period of time, protons emitted from the sun were observed in the terrestrial atmosphere by detectors in the Injun satellite which, by fortunate coincidence, had been placed in orbit only a few days before the start of the disturbances.¹ It is the purpose of this discussion to relate these proton events to other solar-terrestrial phenomena, the findings representing some results of a cooperative analysis being made by G. F. Pieper, C. O. Bostrom, and the writer at APL and B. J. O'Brien at the State University of Iowa (SUI).

The Injun satellite was built under the direction of J. A. Van Allen and B. J. O'Brien of SUI, and contained silicon *p-n* junction detectors designed by G. F. Pieper and C. O. Bostrom. It was launched with Transit 4A on June 29, 1961, and attained an orbit of 67° inclination, with an apogee of 620 miles and a perigee of 550 miles. Injun, with its high-inclination orbit, is well suited to studies of such solar-terrestrial phenomena as those observed in this period, since it crosses magnetic lines of force that intersect the auroral zones where such disturbances are greatest.

Some Solar and Geophysical Phenomena

A flare is a sudden brightening of the solar surface normally viewed in a specific spectral line, such as H α (6563 Å) of atomic hydrogen, where a tenfold increase of intensity is often observed. During the brightening, the spectral intensity rises to a maximum in a few minutes and then decays for periods extending from one-half to several hours, depending on the type of flare; with regard to spatial extent, the flare area may be as much as a billion square miles. The flare classification extends from importance 1 to 3+ in order of increasing area and intensity. Flares of importance 2 and above are frequently associated with a variety of geophysical effects caused by electromagnetic and corpuscular emissions from the sun.

Flare-related Lyman- α radiation (1215 Å) and X-rays² produce an enhancement of ionization in the terrestrial atmosphere. This results in sudden ionospheric disturbances such as fade-out of radio transmissions in the 5-20 mc/sec range, absorption of cosmic radio noise at 27.6 mc/sec, sudden phase anomalies along the propagation path of very low-frequency (e.g., 16 kc/sec) radio waves, and increased ionospheric currents with attendant magnetic variations. Solar radio emissions in the range of 30 to 38,000 mc/sec occasionally occur during large

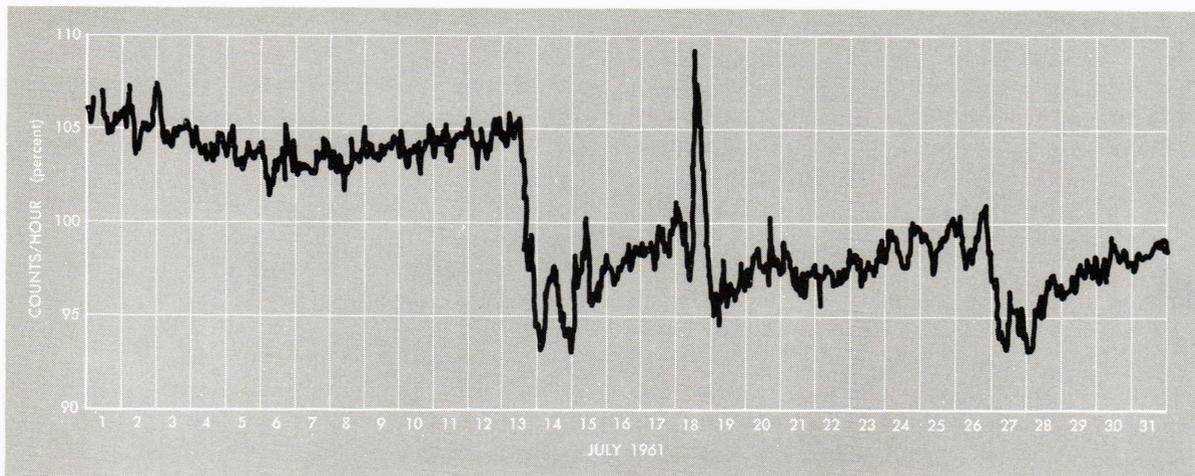
¹ G. F. Pieper, "Injun, A Radiation Research Satellite," *APL Technical Digest*, 1, 1, Sept.-Oct. 1961, 3-7.

² H. Friedman, "The Sun's Ionizing Radiations" in "Physics of the Upper Atmosphere," ed. by J. A. Ratcliffe, Academic Press, New York, 1960.

A number of significant solar phenomena during July 1961 were observed by the Injun satellite, providing valuable new data for the geophysicist. Protons emitted by the sun were studied for several active periods within the month, permitting quantitative analysis of the proton flux under both quiet and disturbed magnetic conditions.

and SOLAR PROTONS in July 1961

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Pressure-corrected hourly totals from the standard neutron monitor at Deep River, Ontario; 55,500 counts per hour correspond to the 100% level. (After H. Carmichael and J. Steljes, "Solar-Geophysical Data," Central Radio Propagation Laboratory Report F-205, Sept. 1951.)

flares.³ These radio outbursts are randomly polarized and last for periods of minutes to tens of minutes.

The solar corpuscular emissions consist primarily of protons and electrons, with energies ranging from a few to a billion electron volts and varying with the type of flare. In addition to pervading interplanetary space where it deflects the primary cosmic-ray flux, the solar stream interacts with the terrestrial atmosphere and magnetic field, producing a variety of geo-

physical effects. One of these is a depletion followed by an enhancement of the electrons trapped in the outer Van Allen belt,⁴ that is, in the belt whose equatorial boundaries lie approximately at altitudes of 2 and 3 earth radii above the earth's surface. Secondly, the particles are deflected into the polar regions where, through collisions with the atmospheric constituents, they produce the excitations yielding the aurora and the ionization responsible for the absorption of cosmic radio noise. In addition,

³ H. W. Dodson, "Solar Flares: Photometry and 200 Mc/sec Radiation" in "The Sun," ed. by G. P. Kuiper, The University of Chicago Press, Chicago, 1953.

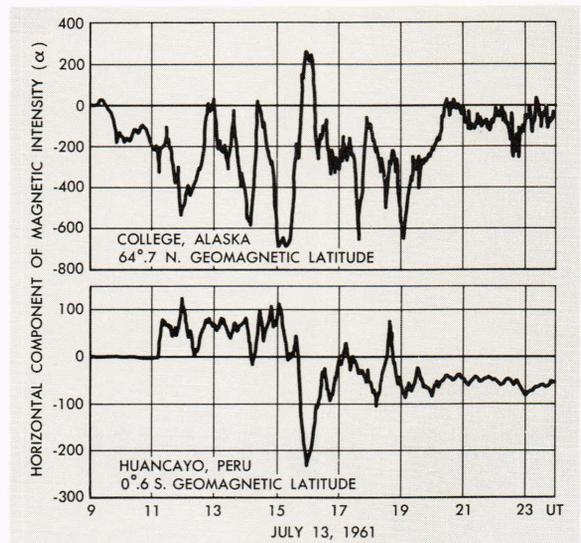
⁴ J. A. Van Allen and W. C. Lin, "Outer Radiation Belt and Solar Proton Observations with Explorer VII During March-April 1960," *J. Geophys. Research*, 65, 1960, 2998-3003.

under the influence of the geomagnetic field the charged particles form the current systems producing magnetic storms.

The primary cosmic rays, which come mainly from sources in our own galaxy, consist almost exclusively of positively charged particles, with protons the predominant component but also containing nuclei of the elements up to and including iron. Near the earth, the deflection of the particles by the terrestrial magnetic field results in a number of well-known geomagnetic effects, including the variation of cosmic-ray intensity with latitude and longitude. Approximately one day after some large flares followed by magnetic storms, there occurs a sharp decrease, termed the Forbush decrease, in the intensity of the primary cosmic-ray flux.⁵ This decrease, which is world-wide, stems from the deflection of the primary cosmic rays by the electromagnetic fields associated with the corpuscular streams ejected from the sun during the flare. The cosmic-ray variations for July 1961 are illustrated here in terms of the variation of the secondary neutrons produced when the primaries collide with the atmospheric constituents. Diminutions are particularly pronounced on July 13 and 27; the relatively large increase on July 18 is due to solar protons of energy approximately 1 Bev which penetrated to the earth's surface.

Magnetic storms are intense magnetic disturbances which frequently start suddenly all over the earth and last for as long as four days.⁶ In middle and low latitudes, during the initial phase of a storm, the horizontal component H of magnetic intensity is increased for a period of 2 to 4 hours. This component then decreases, attaining a minimum generally more below the prestorm value than the positive maximum was above it. From the minimum, the field recovers at differing rates toward the undisturbed level. The main phase of the storm encompasses the period during which H is depressed and the rate of recovery is not increasing; the stage following the main phase is referred to as the phase of recovery. The vertical component of the geomagnetic field undergoes changes much smaller than those of the horizontal component; similarly, the magnetic declination shows little variation during the storm, indicating that the lines of force of the disturbing field lie practically along geomagnetic meridians.

⁵ S. Forbush, "World-Wide Cosmic-Ray Variations, 1937-1952," *J. Geophys. Research*, 59, 1954, 525-542.
⁶ S. Chapman and J. Bartels, "Geomagnetism," Oxford University Press, London, 1940.

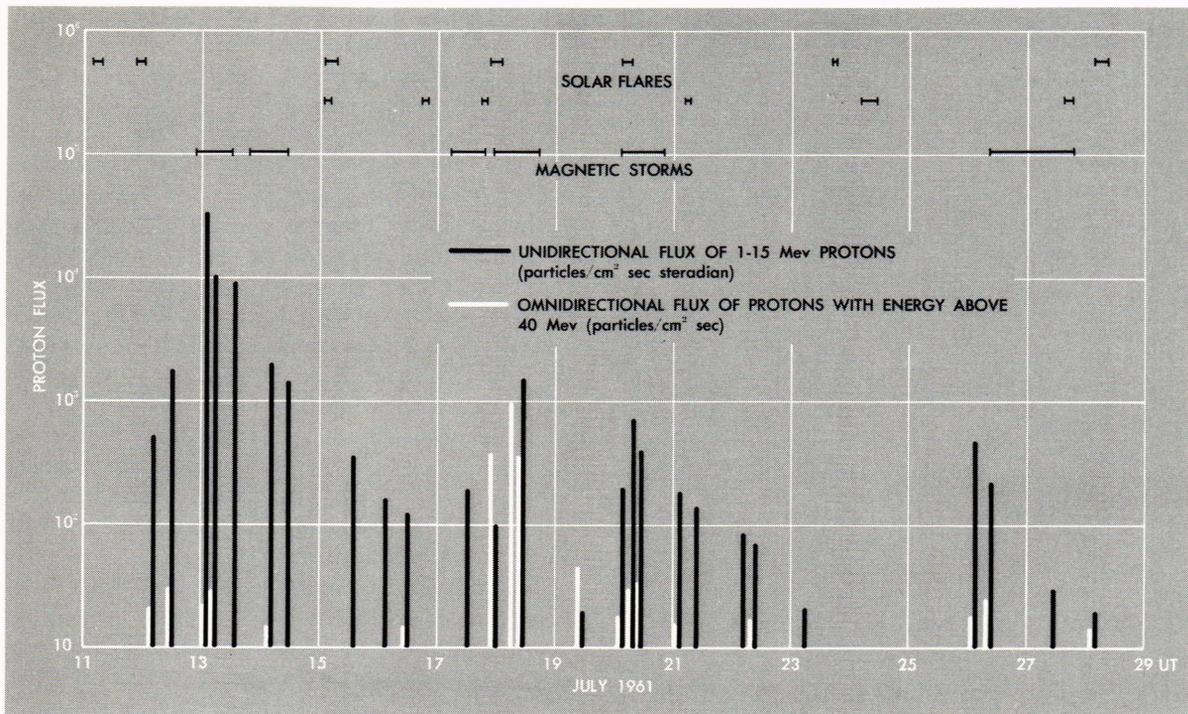


Copies of horizontal component magnetograms for the sudden commencement of the magnetic storm of 1115Z on July 13 (1 gamma = 10^{-5} oersted).

In the polar, and in particular the auroral, regions, the storm variations in all magnetic elements are much greater in amplitude and are far more irregular than those found in lower latitudes. This is shown in the second illustration in the contrast between the horizontal changes at College, Alaska, and Huancayo, Peru.

With regard to the currents producing the magnetic disturbances, the initial-phase field increase at middle and low latitudes stems from currents induced in the frontal surface of the solar plasma as it enters the geomagnetic field.⁷ The main phase relates to a current (generally called a ring current) associated with the induced magnetic moment and east-west drift of the particles temporarily trapped in the geomagnetic field.⁸ (The total motion of a charged particle in the geomagnetic field includes a circular movement about the lines of force and an azimuthal drift normal to the field. The circular motion produces a diamagnetic moment, and the east-west drift yields a transverse current.) In the auroral regions the disturbances are augmented by ionospheric currents driven by electrostatic fields set up by particles impinging into relatively low ionospheric altitudes.⁹

⁷ S. Chapman and V. C. A. Ferraro, "The Theory of the First Phase of a Geomagnetic Storm," *Terrestrial Magnetism and Atmospheric Elec.*, 45, 1940, 245-268.
⁸ J. R. Apel, S. F. Singer, and R. C. Wentworth, "Effects of Trapped Particles on the Geomagnetic Field," U. of Md. Tech. Rept. 237, Dec. 1961.
⁹ E. H. Vestine, "Polar Auroral, Geomagnetic, and Ionospheric Disturbances," *J. Geophys. Research*, 65, 1960, 360-362.



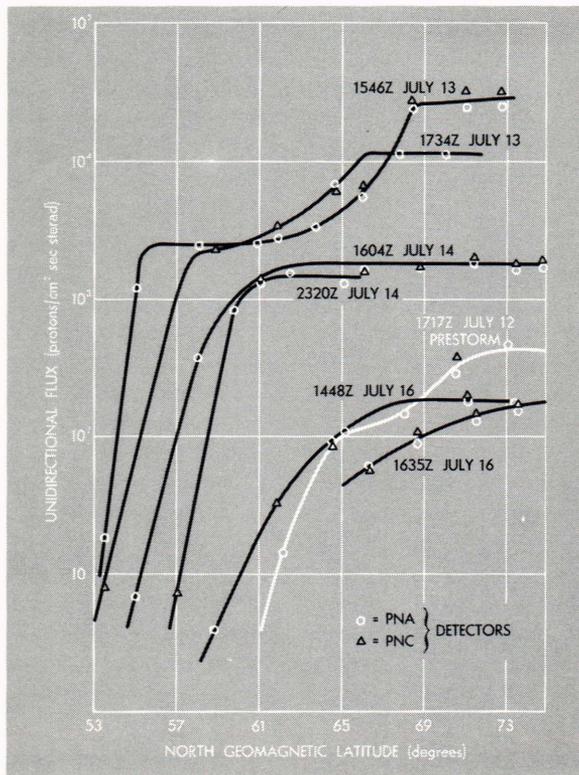
Maxima of the proton flux detected at different times during the July period of solar and terrestrial disturbances. The temporal extent of the solar flares and magnetic storms is also shown.

Solar Proton Study

The period from July 1 to 11 was one of solar and magnetic quiet, with only one storm and without any flares of importance 2 or 3 until that of 1615Z (or 4:15 PM) on July 11. (Universal time is used here exclusively; it refers to local time at Greenwich, England, and is frequently designated by U.T. or Z.) This was a flare which marked the beginning of a period of considerable activity extending to July 28 and containing 13 flares of importance 2 or 3 and six major magnetic storms. During this active period, the Injun satellite on many occasions detected protons that were contained in the solar corpuscular stream. The temporal and spatial variations of the proton events, in relation to solar flares and magnetic storms, are shown in two illustrations. For the Injun analysis, the solar protons can be divided into two energy ranges—from 1-15 Mev and beyond 40 Mev. Here we treat mainly the 1-15-Mev interval, which is covered by the two APL silicon *p-n* junction detectors, mounted orthogonally, and referred to as PNA and PNC in the last illustration.

The first observation of solar protons by Injun occurred on the northward pass of 1717Z

on July 12, eighteen hours before the sudden commencement of a magnetic storm. The protons started to appear at a north geomagnetic latitude of 61° and rapidly increased in number with increasing latitude, reaching a maximum unidirectional flux of $450 \text{ protons/cm}^2/\text{sec/steradian}$ at about 71° . Unidirectional proton flux refers to the number of protons per unit solid angle crossing a normal area of 1 cm^2 in 1 sec. High-latitude proton counts also existed during the pass of 0034Z on July 13, in this case beginning at 60°N and extending to 67°N , the highest latitude for which data are here available. Telemetry of the subsequent pass showed that there were no solar protons in the geomagnetic latitude range of 34° to 58°N . Since these three passes occurred during the quiet magnetic period preceding the storm that began at 1115Z on July 13, the proton flux here detected was the forerunner of the plasma stream producing the storm; the data for the pass of 1717Z on July 12 show, under quiet conditions, the latitude effect at 600 miles for solar protons in the energy range of 1-15 Mev. One notable feature is the sharp rise at 61° associated with the geomagnetic cutoff. (Because of the deflecting force of the geomagnetic



Latitude-dependence of solar protons in the energy range of 1-15 Mev and in relation to the magnetic storms of 1115Z on July 13 and 0800Z on July 14.

field, there is a minimum latitude to which a particle of given energy can penetrate. This minimum angle is frequently called the cutoff or critical latitude.)

During the entire period of the first relevant storm, 1115Z on July 13 to 0100Z on July 14, fluxes were detected, indicating that 1-15-Mev protons were also imbedded in the relatively low-energy solar plasma causing the magnetic storm. During the initial phase, extending from 1115Z to about 1530Z on July 13, two passes of Injun showed that protons were present in regions with latitudes above 61°N, as in the prestorm period. This indicates that the initial-phase currents and fields do not drastically change the geomagnetic characteristics which determine the lowest latitude where the protons appear. The maximum flux was 590 protons/cm²/sec/steradian for the pass at 1224Z and 33,200 for that at 1409Z, the latter also representing the maximum flux observed during July; the relatively low flux for the 1224Z pass possibly relates to the condition that this pass extended only to 64°N.

During the main phase of a magnetic storm, when storm particles are temporarily trapped in the geomagnetic field, profound changes occur in the spatial and temporal distribution of the 1-15-Mev protons—variations due to the interaction between these protons and the electromagnetic fields associated with the lower-energy storm particles. There is generally an extension of the proton regions to lower latitudes, as exemplified in the last illustration, in the difference between the prestorm pass of 1717Z on July 12 and the main-phase passes of 1546 and 1734Z on July 13 where, for example, the critical geomagnetic latitude shifted from 61° to 53°. In addition, with reference to the plateau regions of the latter two passes, the proton flux decays exponentially during the main phase, with a time of 1.4 hours required to decay by a factor of e^{-1} (relaxation time).

The sudden commencement of the storm at 1115Z on July 13 was followed by a gradual storm beginning at 0800Z on July 14 and producing principally a depression of the geomagnetic field without any preceding initial field rise. During this storm, three successive passes yielded practically identical results characterized in the data of 1604Z on July 14. The gradual storm ended at 2400Z on July 14 and was followed by a period of magnetic quiet extending to 1830Z on July 17. During the poststorm period, the particle flux decayed with a relaxation time of 20 hours, and the latitude-dependence shifted toward, and ultimately returned to, the prestorm condition. At this time it is not clear whether the protons detected in this quiet period represent particles injected during the preceding storms and temporarily trapped in the geomagnetic field or new particles leaking into the geomagnetic field from interplanetary space.

In the last 10 days of this period of disturbance, July 18 to 28, in which four magnetic storms were recorded, additional solar protons were detected. These had spatial and temporal characteristics similar to those found in the prior period but with a considerably reduced peak intensity.

In general, protons emitted by the sun represent one facet of an array of complex solar and geophysical phenomena. Their detection by Injun in such abundance and at high latitudes permitted for the first time a quantitative analysis of the proton flux and its variation in the geomagnetic field during quiet and disturbed magnetic conditions.