Solar Cosmic Ray 'Square Wave' of August 1972

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Three Rice University suprathermal ion detector experiments (Sides) were deployed on the lunar surface during the Apollo 12, 14, and 15 missions. During the exceptional period of solar activity in August 1972, penetrating particles were observed by all Side detectors on the night side of the moon. The penetrating particles are tentatively identified as solar protons with energies (~ 25 MeV or greater) that were able to penetrate the shielding of all detectors. Of particular interest is the occurrence on August 5 of a 'square wave' flux enhancement of 2-hour duration. Data from a variety of ground-based and space experiments are examined in relation to the square wave. Based on the results of this investigation a model relating the square wave to the flare plasma propagation is proposed. This model hypothesizes transport of energetic particles along a 'corridor' formed by the tangential discontinuity produced by the driver gas of a flare-induced shock wave. This model could explain other frequently observed delayed particle events.

INTRODUCTION

Early in August 1972 there occurred a series of impressive solar flares. The flares observed during this time were associated with some of the largest emissions of energetic particles ever recorded [McKinnon, 1972; World Data Center A, 1973]. Photospheric magnetograms indicated strong field activity during this period [Livingston, 1972]. Interplanetary space was disturbed with drastic changes in the solar wind [Wolfe et al., 1972; Armstrong et al., 1972; Rosenbauer et al., 1972; Medrano et al., 1973a] and in the interplanetary magnetic field [Colburn et al., 1972; Smith et al., 1972].

In this paper we present the analysis and results of the data taken by the Rice University suprathermal ion detector experiments (Sides) pertaining to one particular penetrating particle feature of the August event. The Sides were deployed on the lunar surface by the astronauts of Apollo 12, 14, and 15 and continuously transmit data to earth on the plasma environment of the moon. Since the Sides were not intended as solar cosmic ray detectors, the information provided by the instruments in this event is necessarily crude; however, the significance of the results to be discussed is not diminished.

COSMIC RAY RESPONSE OF THE SIDES

Each Side instrument consists of two detectors, a mass analyzer (MA) and a total ion detector (TID). Together these measure the differential fluxes of positive ions in the energy range 0.2–3500 eV per unit charge. The sensors for these detectors are funnel-type channel electron multipliers manufactured by the Bendix Corporation. The channel electron multipliers have their entrance apertures biased at -3500 V and hence can collect, accelerate, and count low-energy ions generated in or near the input funnel by penetrating radiation traversing the instrument side walls. The detectors thus become crude cosmic ray monitors. Further details of the Side design are given by Freeman et al. [1972] or Hills and Freeman [1971]. The Sides deployed at the three Apollo sites (12, 14, and 15) are essentially identical.

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The shielding in the detector side walls is a complicated function of direction, since the absorbing material consists of electronic components, encapsulation material, thermal paint, etc. Accordingly, we have calculated the minimum energy that protons must have to penetrate to the sensor. We find that approximately 25-MeV protons are able to penetrate to the MA and 50-MeV protons to the TID. The equivalent numbers for electrons are 1.4 and 4.7 MeV, respectively.

To check these calculations, we placed a spare Side instrument in a cyclotron proton beam of 50-MeV maximum energy. The results indicated these to be good working numbers to within 50%. The cyclotron beam could not be used for absolute efficiency calibrations because of the short duration of the cyclotron beam pulse.

As a further independent check on the energy thresholds of the MA and TID detectors we have compared data on solar particle decay times with results from the proton detector aboard the Imp 5 and Imp 6 spacecraft [Kohl et al., 1973]. These results indicate thresholds of 32 ± 7 MeV and 73.5 ± 17 MeV for the MA and TID, respectively.

The area of the channel electron multiplier funnel is approximately 0.5 cm^2 . At 100% efficiency this yields an omnidirectional geometric factor G_0 of 0.5 cm^2 . The quiet nighttime background count rate of four of the six sensors is usually about 0.5 c/s or less. This is consistent with the calculated G_0 and with most of the background being due to galactic cosmic rays.

During a separate solar cosmic ray event we compared the background count rate registered by the Side detectors with the omnidirectional solar proton flux measured by the ATS 1 spacecraft. In this case we found $G_0 = 1.2 \pm 0.8 \text{ cm}^2$. There are two reasons to suspect that this G_0 is too high. First, the ATS 1 detector provided no information on protons above 70 MeV, and second, the investigators have reported the possibility of sensor degradation in the ATS 1 detectors [World Data Center A, 1972].

A more careful analysis of the galactic cosmic ray flux using the differential energy spectra of several investigators [Comstock et al., 1972] compared with the long time average of the Side detector backgrounds taken on the night side of the moon gives the result $G_0 = 0.3 \text{ cm}^2$. We favor this result and believe it to be applicable to the August 1972 event to within a few factors of 2.

Figure 1 shows the location of the moon at the time of local

Fig. 1. Lunar orbit and the positions of the moon at the local sunsets of Apollo 12, 14, and 15. The data reported in this paper were obtained between the two positions where the detector look directions are indicated. The geomagnetic cavity is shown for reference, and the positions of the Imp 5 and Heos 2 spacecraft on August 5 are indicated by 15 and H2, respectively.

sunset at the Apollo 12, 14, and 15 sites early in August 1972. Table 1 gives the times of local sunset and the angular distances past the sunset terminator for each of the sites. It is seen that all three sites are well onto the night side of the moon by 0400 UT on August 5. The Apollo 12 and 14 sites are 138 km apart and in global terms can be considered to be at the same location. Apollo 15 is 1100 km away.

SIDE OBSERVATIONS

The complete results of the Side experiments during the August 1972 solar events have been reported by Medrano *et al.* [1973a, 1973b]. For review, we will here summarize the penetrating particle results shown in Figures 2 and 3.

Starting at 0730 UT on August 4, 1972, the background count rates of each detector in all three Sides increased abruptly. The count rates remained elevated for approximately 3 days and passed through a maximum some 6–14 hours after the onset. The maximum counting rate exceeded by three orders of magnitude the background associated with galactic cosmic rays. This burst of solar cosmic rays is attributed to the class 3B flare which began at 0520 UT on August 4 [World Data Center A, 1972]. The transit time for the initial flare particles is then 2 hours and 10 min.

A second similar abrupt increase was seen on August 7 at 1547 UT. This enhancement was 2 orders of magnitude less intense and lasted only 2 days. The flare associated with this burst was the 3B flare that began at 1445 UT, indicating a transit time of 1 hour and 2 min.

The purpose of this paper is not to discuss these general enhancements but rather a most interesting feature of these penetrating particle events, a "square wave" flux enhancement that started at 0310 UT and ended at 0459 UT on August 5. This feature is shown in detail in Figure 4. The rise and fall times for this square wave were both about 8.5 min. It was preceded by a precursor spike at 0259 lasting only 7 min. There is no flare feature reported that can be directly associated with this interesting event. The flux enhancement indicated is about one order of magnitude above the decreasing penetrating particle flux from the first 3B flare.

RELATED SQUARE WAVE OBSERVATIONS

The square wave under discussion was seen by experiments aboard several spacecraft near the earth: the Imp 5 and Imp 6 [Kohl and Bostrom, 1972; Bostrom, 1973; Lanzerotti and MacLennan, 1973] and the ATS spacecraft [Paulikas *et al.*, 1972]. Another particle experiment on the lunar surface also recorded the square wave [Moore *et al.*, 1973]. Pioneer 9 and 10 did not see it; however, they were located at 46°E from the earth-sun line at 0.8 and 2.2 AU, respectively [Lezniak and Webber, 1972; Webber *et al.*, 1972].

Among the experiments that saw the square wave there was generally good time correlation when transit and diffusion times are taken into consideration. A puzzling exception is the slightly early end to the square wave at the moon compared with Imp 5 data (C. Bostrom, private communication 1973).

Interplanetary magnetic field data from Heos 2 (P. Hedgecock, private communication) and Explorer 41 [Venkatesan *et al.*, 1975] indicate a significant change in the field vector during the passage of the square wave. The field was roughly radially outward both before and after but changed polarity to radially inward during passage. Also there existed a strong component north of the ecliptic before and after. This disappeared during passage [Bostrom, 1973].

During the first days of August 1972, ground-based neutron monitors recorded large variations in the cosmic ray intensity. Figure 5 illustrates hourly data from several stations. During the early morning of August 5 the neutron monitors observed a transient feature similar in appearance to the square wave recorded by lower-energy detectors in space. Figure 6 illustrates the detailed features of this transient increase as recorded by the Sulphur Mountain neutron monitor. This enhancement was due to relativistic particles of solar origin or galactic origin or particles accelerated in the interplanetary medium. A galactic origin is indicated by the following evidence:

1. The ratios of the amplitudes of this transient feature from pairs of nearly adjacent neutron monitors at differing altitudes (e.g., Sulphur Mountain and Calgary, McMurdo, and South Pole) are close to those recorded during short-term modulations of the galactic intensity rather than during solar particle events.
2. Equatorial stations responded to this transient, whereas solar particle events are generally apparent only at polar stations (e.g., the solar particle event on the preceding day).
3. The spectrum of the transient increase derived from data from underground detectors is estimated to vary as about $E^{-1.6}$ [Sekido *et al.*, 1973] and was seen underground at 20 m water equivalent (i.e., $E = 70\text{--}100\text{ GeV}$) [Filippov *et al.*, 1973].

TABLE 1. Deployment Characteristics of Alsep-Sides on Apollo 12, 14, and 15 and Angular Distances From the Terminator at the Time of the Solar Cosmic Ray Square Wave

	Apollo 12	Apollo 14	Apollo 15
Time of local sunset			
Hour	0348 UT	1706 UT	2338 UT
Date	Aug. 4	Aug. 3	Aug. 1
Alsep selenographic coordinates			
Latitude	3.2°S	3.7°S	26.01°W
Longitude	23.4°W	17.5°W	3.6°E
Angular distance past the sunset terminator at 0400 UT Aug. 5	11.9°	17.6°	36.0°

Fig. 2. Time history of the penetrating particle event. Every row of blocks displays 3 days of data from each Apollo experiment. The counts per second, plotted on a logarithmic scale, very nearly represent also the omnidirectional flux in particles $\text{cm}^{-2} \text{s}^{-1}$. MA and TID represent protons with energies of ≥ 25 MeV and ≥ 50 MeV, respectively.

In contrast, the preceding solar particle event on August 4 had a spectrum with an exponent between -5 and -6 [Pomerantz and Duggal, 1973].

The transient increase in the neutron monitor variations therefore appears to manifest features which are typical of a short-term modulation of the galactic intensity. A solar origin for this enhancement at the energies responsible for neutron monitor variations has been rejected by other workers [e.g., Pomerantz and Duggal, 1974; Agrawal et al., 1974].

DISCUSSION OF THE RESULTS

The solar activity of the first half of August 1972 consisted of at least four major solar flares as observed in the Ly α line. All four flares were produced by the same region of activity (McMath plage region 11976). The first flare (of importance 1B) started at 0316 UT on August 2, and it took place at 13°N and 35°E on the sun. It generated a shock wave which was probably registered by Pioneer 9 between 1100 and 1500 UT

Fig. 3. Time history of the penetrating particle event. See Figure 2 legend for details.

Fig. 4. Square wave enhancement as seen by the TID of the Apollo 14 Side on August 5, 1972. A nearly identical square wave structure was seen by the other Side detectors. The counting rate very nearly represents the omnidirectional flux in particles $\text{cm}^{-2} \text{s}^{-1}$ of protons of ≥ 50 MeV.

on August 3 and produced an sc on earth at 0119 UT on August 4 (see Figure 7). Pioneer 9, which was at 46°E and at 0.8 AU, observed a significant enhancement in the proton fluxes between 0730 and 1200 UT on August 2. Detectors on board Imp 5 and Imp 6 noticed a gradual increase in their lowest energy (>10 MeV) threshold detector at 0945 UT [Kohl *et al.*, 1973].

A second flare (of importance 2B) produced another shock wave which probably was overtaking the previous shock when it passed the earth. The mean speed of the shock at 0.8 AU derived directly from the transit time is 1740 km/s. The bulk speeds measured by Pioneer 9 at 1100 and 1500 UT were 350 and 585 km/s, respectively. If these values were representative of the preshock and postshock conditions and if we assume a jump in the number density by a factor of 10 (a reasonable assumption for strong shocks), we can make an estimate of the possible shock speed. In the stationary reference frame of the propagating shock, mass conservation requires

$$n_1(V_1 - U) = n_2(V_2 - U)$$

where n_1 , V_1 and n_2 , V_2 are the number density and speed of the solar wind on both sides of the shock front and U is the shock speed for a radial propagation. Under the assumptions mentioned above we estimate $U \approx 610$ km/s, which is lower than that derived from the mean transit time. Using adjacent extreme values ($V_2 = 730$ km/s, $V_1 = 290$ km/s), we find an upper limit $U \approx 780$ km/s. This implies a shock deceleration by the ambient plasma, as is currently accepted [Gosling *et al.*, 1968]. If the shock deceleration from 0.8 to 1 AU were not important (the energy density of the solar wind decreases as $1/r^2$ as one goes out from the sun), the shock would propagate to the earth's orbit in approximately 10 hours. However, the time between the first measured jump in the wind speed by Pioneer 9 and the sc on earth was more than 12 hours. This simple calculation gives us an idea of the nonspherical propagation of this shock.

Solar proton events apparently were not exceptionally important during these first two flares, at least not at the earth's position.

The flare of August 4 at 0530 UT produced one of the

strongest plasma and solar cosmic ray events ever recorded. The flare was located at 14°N and 09°E on the sun. The observed onset of the solar protons corresponding to this flare was between 0400 and 0800 UT in Pioneer 9 and at around 0730 UT in the Alsep-Sides, Alsep-CPLEE, and the Imp 5 and Imp 6 experiments. Since the location of the flare was slightly to the east of the sun's central meridian, these protons might have reached the detectors by diffusion processes. The shock wave originated by this flare was presumably observed by Pioneer 9 between 2000 and 2400 UT on the same day of the flare. The Heos 2 magnetometer and ground-based magnetometers recorded a jump in the interplanetary magnetic field vector at about 2100 UT. The transit time of this shock implies a very high mean speed of propagation (2410 km/s) which is not commonly observed [Hundhausen, 1970]. About 6 hours later (at 0230 UT on August 5) Heos 2 measured a significant change in the magnetic field magnitude and direction. After a short delay the solar proton fluxes at the moon increased sharply and stayed almost constant for about 2 hours and then decreased suddenly down to the level of the normal decay (see Figures 2 and 3). The time interval between the observations of the magnetic field discontinuity by Heos 2 and the onset of solar proton fluxes detected by the Side instruments was 30 min. This is only a short time (less than 3 min) longer than the time a corotating region in space would take to reach the moon's position starting at the Heos 2 satellite's relative position. (The moon's instantaneous position can be visualized in Figure 1, and the Heos 2 was at 138.96° and 32.66° geocentric solar ecliptic longitude and latitude, respectively, and at $33 R_E$ from the earth.) The Side instruments were past their local sunsets during this time; therefore the moon shielded them from particles flowing directly from the sun. However, the interplanetary magnetic field lines are bent and piled up at the magnetosphere on the day side [Spreiter *et al.*, 1966], forming a tangential discontinuity that is commonly known as the magnetopause. Solar protons following interplanetary field lines as guiding centers could mirror at the magnetopause depending on their pitch angle and head back upstream toward the sun. This may be the method by which the square wave protons reached the dark side of the moon.

The observed interplanetary magnetic field discontinuity can be identified with the surface that separates the ambient (disturbed) plasma and the plasma released by the flare from the chromosphere. The driver gas normally appears to follow the shock wave by 5–12 hours [Hirshberg *et al.*, 1970]. Theoretical considerations [Hundhausen, 1972] indicate that the surface that separates the ambient plasma (i.e., the transition region) and the plasma released by the flare is a tangential discontinuity. A detailed analysis of one of these driver gas tangential discontinuities has been made by Medrano [1973]. It seems reasonable to assume that the magnetic discontinuity observed by Heos 2 at 0230 UT on August 5 was the signal of the driver gas arrival. The field lines of the discontinuity on the side of the driver gas connect directly to the center of activity of the flare. These interplanetary field lines have small-scale irregularities convected from the chromosphere which are the major cause for the cosmic ray perpendicular diffusion. If there exist mechanisms that smooth these irregularities, then the perpendicular diffusion of the energetic particles would be reduced. (Possible smoothing mechanisms will be mentioned later.) Under these circumstances the tangential discontinuity is transformed into a 'free corridor' for the propagation of energetic charged particles. Therefore if the flare site is still actively injecting energetic particles [Roelof and Krimigis, 1973],

these will follow the tangential discontinuity field lines. When this corridor sweeps past the earth, it would cause a square wave like enhancement in the proton fluxes measured by a spacecraft.

The rise and fall times of the square wave, as measured by the Side instruments, correspond to a thickness of about 7×10^6 km, whereas the gyroradius of a 50-MeV proton in a 30- γ

field (measured by Heos 2) is 3×10^6 km. Assuming that the magnetic corridor was free of inhomogeneities, the rise time of the square wave would be expected to be related to a few gyroradii of the solar protons. Since the actual thickness is only slightly larger (by about a factor of 20) than the gyroradius, little diffusion through the sides during transit from the sun is indicated.

Fig. 5. Percentage variations of the galactic cosmic radiation as recorded by a selection of ground level neutron monitors. Variations are plotted with the same vertical scale as a function of time in UT. For each station the geographic coordinates and vertical cutoff magnetic rigidity are given. In the rightmost column we illustrate the asymptotic viewing directions (in geographic coordinates) of higher magnetic rigidities.

Fig. 6. Illustration of the different time variations recorded during the morning of August 5, 1972, by detectors responding to cosmic rays of different mean primary energy for (top) Yakutsk mesons at 60 m water equivalent and (bottom) Sulphur Mountain neutrons. Five-minute data from the Sulphur Mountain neutron monitor reveal a short-lived recovery peak at primary energies of a few GeV; in the hundreds of GeV primary energy range ($E = 200\text{--}280$ GeV), the underground meson monitor at Yakutsk registers a decrease late in the morning. Data from Sulphur Mountain are reproduced by courtesy of T. Mathews; Yakutsk data are reproduced from *Filippov et al.* [1973].

The relativistic particles observed by the ground-based neutron monitors can be related to the magnetic discontinuity and corridor in one of two ways. The first possibility is that these relativistic particles are of solar origin and are simply a high-energy extension of the spectrum of solar particles in the square wave recorded by the detectors in space. This interpretation, however, implies continuous injection of relativistic (GeV) particles at the flare site even hours after the original burst. Since this does not appear to be experimentally confirmed, we are unable to state any definite conclusion regarding this possibility.

A second possible interpretation is that the square wave enhancement recorded by the neutron monitors results from a short-term modulation of the galactic cosmic ray intensity. Let us assume that the transient increase is the result of the superposition of two sequential Forbush decreases. Around 2200 UT on August 4 a very large Forbush decrease occurred. The existence of a second Forbush decrease mechanism operative at high primary energies is indicated by the Yakutsk underground data presented in Figure 6. It will be noted that this detector hardly responded at all to the huge Forbush decrease late on August 4 but recorded a second Forbush decrease in the late morning of August 5. In the light of the observations therefore we are led to postulate that the first Forbush decrease was caused by the passage of the earth through a shock front, the transient increase by the passage through a region being replenished with galactic cosmic rays by means of parallel diffusion along the tangential discontinuity, and that the increase was terminated by the entry into a closed loop structure capable of excluding cosmic rays up to very high energies. Recently *Barnden* [1973] has independently arrived at similar conclusions in his analysis of the September 1966 and December 1971 events. Such an interplanetary magnetic configuration is consistent with and substantiated by the evidence that the relativistic particle square wave results from modula-

tion of galactic cosmic rays. The lower-energy square wave seen by detectors in space is certainly of solar origin.

MODEL OF PROPAGATION

At this point we present a model representing the dynamics of the particles and fields in the interplanetary space corresponding to the solar proton square wave of August 5, 1972.

The model is based on the current and generally accepted picture of a shock and blast wave propagation following a solar flare [*Hundhausen*, 1972]. Fresh plasma supersonically ejected during a flare propagates through the ambient plasma. Due to the highly conductive nature of both plasmas, interpenetration is forbidden, so the ambient plasma and field lines accumulate in front of the fresh plasma. Consequently, a shock wave is built up ahead of the driver gas. Between the shock and the driver gas there exists a transition region where both the ambient plasma and fields are highly disturbed. Between the transition region and the fresh plasma a tangential discontinuity exists. The field lines on the side of the driver gas at the tangential discontinuity connect directly to the center of activity of the flare. If this center of activity continues to inject energetic protons, these protons will propagate with their guiding centers following the field lines of the discontinuity. Furthermore, if the field lines are free of inhomogeneities (an idealized case), the discontinuity will provide a type of free corridor for the propagation of energetic solar protons. Figure 7 is an artistic representation of the shock wave propagation several hours after the flare. The tongue-shaped flare plasma ejected follows the description made by *Hundhausen* [1972] and is based upon the observations. The solar proton corridor follows the tangential discontinuity. The spreading of the particles on the sides of the corridor is due to the diffusion across field lines. Figure 8 is intended to illustrate the geometry of the event some days later. An observer at the point A will traverse the corridor noticing a

Fig. 7. Sketch of the propagation of a flare-induced shock wave several hours after the flare time [after *Hundhausen*, 1972]. Energetic solar protons (solar cosmic rays) propagate along the tangential discontinuity formed by the fresh plasma. Gradual diffusion perpendicular to the field lines makes the population of the solar protons extend over the shaded area (observed to be 7×10^5 km at 1 AU).

square wave like enhancement in the cosmic ray fluxes. Another observer at the point B will notice a solar proton flux enhancement that is less intense than A but occurs over a longer period of time.

According to this model, after a major solar proton flare an enhancement in the solar cosmic ray fluxes should be expected before (observer B) or with (observer A) the arrival of the tangential discontinuity. The time and the shape of this enhancement will depend not only on the heliographic coordinates of the flare but also on the diffusion processes across field lines. If the perpendicular diffusion of charged particles were mostly due to the uneven configuration of the field lines along the general pattern, then this type of diffusion could be expected to be inversely proportional to the solar wind speed. The smoothing of the interplanetary field lines by the solar wind can be analogized by a rubber band fixed at both extremes across a river. The speed of the fluid controls the smoothness and distention of the rubber band. This type of smoothing can be carried out by MHD waves (primarily Alfvén waves) propagating from the sun along the tangential discontinuity. The wave activity is likely to be enhanced at the surface of the discontinuity by the speed of the driver gas. Another smoothing mechanism can be provided by the pressure exerted on the field lines by the energetic particles injected at the flare site. Both of these mechanisms are currently under investigation.

The square wave particle enhancement on August 5 must have had little diffusion across field lines, since its rise and decay times are small (only about 20 times the equivalent Larmor radius). This unusually small perpendicular diffusion is probably due to the remarkably high speed of the wind and unprecedented emission of solar cosmic rays.

The width of the square wave (2 hours and 8 min) corresponds to 0.07 AU. This shell is within the range of the estimated thickness of a helium-enriched region in front of the driver gas [*Hundhausen*, 1972]. Because of the lack of solar wind data we cannot confirm this suggestion.

Enhancements in the solar proton fluxes in association with

the sudden storm commencements and Forbush decreases have been reported in the literature [*Bryant et al.*, 1962; *Axford and Reid*, 1962; *Lockwood and Razdan*, 1963; *Haurwitz et al.*, 1965; *Ahluwalia*, 1966; *Kahler*, 1969; *Engelmann et al.*, 1969; *Ogilvie and Arens*, 1971; *Balogh et al.*, 1971; *Datlowe*, 1972]. Several interpretations including trapped solar protons behind the shock front [*Bryant et al.*, 1962; *Haurwitz et al.*, 1965], acceleration in the transition region [*Axford and Reid*, 1962; *Datlowe*, 1972], temporary leakage of galactic cosmic rays through the plasma cloud under 'certain instabilities' [*Lockwood and Razdan*, 1963], etc., have been made. However, these models bear some inconsistencies with the observations [*Datlowe*, 1972].

A difficulty in the present model is that it assumes continuous injection of energetic particles. Long-lived solar proton streams of MeV energies for as much as a complete solar rotation have been reported by *Bryant et al.* [1963]. Recently *Roelof and Krimigis* [1973] have lent new support to the idea of time-extended injection. It seems to us that continuous injection of energetic protons at the flare's center of activity is the most favorable explanation at this time.

SUMMARY AND CONCLUSIONS

Data analysis of the Alsep-Side experiments of Apollo 12, 14, and 15 has been made in relation to the solar activity of early August 1972. Observations of solar wind ions during this active period are reported in other works [*Medrano et al.*, 1973a, b; *Medrano*, 1973]. While the solar wind activity was still in progress, solar cosmic ray protons with fluxes never before seen by Side arrived on the night side of the moon. The estimated minimum energies for these protons to penetrate the shielding of the MA and TID detectors are 25 MeV and 50 MeV, respectively. The observations of the solar proton event can be summarized as follows:

1. Two major enhancements in the solar proton fluxes are directly related to two solar flares: 3B on August 4 at 0525 UT and another 3B flare on August 7 at 1445 UT. During this time the Side experiments were in the lunar night and could not observe directly protons coming from the sun. It is suggested

Fig. 8. Sketch of the propagation of a flare-induced shock wave several days after the flare time. The diffusion of the solar protons on the sides of the tangential discontinuity makes their confinement wider than that in Figure 7.

that these protons following the field lines mirrored on the nose of the magnetopause and then headed back toward the sun.

2. A third solar proton enhancement cannot be directly related to any solar flare. It took place at 0310 UT on August 5 during the decay time of the proton event of August 4. The peculiar characteristic of this event is the square wave shape of the enhancement with rise and fall times of 8 min and a duration of approximately 2 hours.

In connection with this last-mentioned singular event, data from a variety of ground-based and space experiments have been examined. The result of this analysis appears to show that the onset of the square wave corresponds to the tangential discontinuity that signals the arrival of the driver gas ejected by the flare of August 4.

A model to explain the square wave particle propagation has been elaborated. The model hypothesizes continuous injection of energetic solar protons into interplanetary space by the active center of the flare site for hours after the flare time. The tangential discontinuity serves as a magnetic corridor for the propagation of the energetic protons and as a mechanism for subsequent modulation of galactic cosmic rays. The width of this corridor at 1 AU, as derived from the duration of the square wave, is 0.07 AU. The rise and fall time of the square waves is approximately 20 times larger than the Larmor radius of a 50-MeV proton. This is interpreted as an indication of only slight diffusion across field lines. At larger distances from the sun this diffusion process should be expected to intensify the cosmic ray fluxes in the transition region behind the shock front.

It is suggested that the frequently observed energetic solar protons in association with ssc and Forbush decreases (delayed solar particle events) can be explained by this model.

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