THE CONTINUAL ACCELERATION OF SOLAR PROTONS IN THE MeV REGION

D.A. Bryant*, T.L. Cline, U.D. Desai** and F.B. McDonald
Goddard Space Flight Center
Greenbelt, Md.

The production of solar cosmic rays has previously been associated with discrete events on the sun, generally beginning with a solar flare in an active region and accompanied by a Type IV radio noise burst extending from the microwave to the decametric region. In these events the particle acceleration is assumed to occur on a time scale of a few minutes, short compared to the flare duration of ~ 0.5 to 2 hours. A second type of solar particle emission consists of very low-energy protons in the keV region associated with the coronal expansion which results in the solar wind. We report here evidence for the long-term persistence of a new component consisting of protons in the 3 to 20 MeV region. The lower limit of ~ 3 MeV represents the threshold of our detector and it is expected that the spectrum of this new component probably extends down to much lower energies. These protons are contained in streams of ~ 30 to 120 degree width at the orbit of the Earth and are present over many solar rotations. They have been observed on

* Now at D.S.I.R. Radio Research Station, Slough, Bucks, England
** Now at Physical Research Laboratory, Navrangpura, Ahmedabad, India

at least seven consecutive rotations of the sun with the Goddard cosmic-ray experiment on Explorer XIV in the period February to July, 1963. These recurrence events are characterized by both a very low intensity level (generally several orders of magnitude below that of a moderate-sized solar proton event at these energies) and a very steep energy spectrum. In contrast to the solar proton event, no velocity dispersion is observed among the various energy groups. Thus, when a stream is encountered it is observed that, for example, both 3- and 10-MeV particles are present simultaneously, indicating that a quasi-equilibrium state has been established.

We have previously reported evidence for recurrent solar-proton events[1,2,3] based on the finding that low -energy protons were detected at the times of the next central-meridian passage of each of two active regions which had given rise to solar proton events 21 and 29 days earlier. It was felt that those recurrent events owed their existence to the preceding solar-proton-producing active region. We now judge those events to be similar to the ones reported here. In addition, further observations of recurrent events were made with the University of Chicago cosmic-ray experiment on IMP-I (Explorer XVIII)[4]. On at least three occasions in late 1963 and early 1964, low-energy protons were observed on IMP-I coming from the <u>same</u> region on the sun as we observe on Explorer XIV.

The Explorer XIV cosmic ray experiment[3] consisted of three detectors designed to study galactic and solar cosmic rays. Because the events reported here consisted solely of low energy particles (except for the 1 May event) only the single crystal detector exhibited a response.

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Briefly, this detector consists of a thin CsI (Tl) crystal, 1.9 cm in diameter and 0.5 g/cm^2 thick, covered by a 6.5 mg/cm^2 Al foil. An aluminum collimator with an average thickness of 1.7 g cm^{-2} surrounds the crystal such that the geometric factor for the low-energy protons is 2.85 cm^2 - ster. The photomultiplier viewing this crystal is connected to an 8-level integral pulse-height analyzer. Calibration is provided by a small Pu^{239} alpha-particle source mounted on the front of the crystal. The lowest level of the eight-channel analyzer responds to both electrons and protons. Calibration and appropriate radiation belt data verify that the upper 7 levels exhibited no electron response. The photomultiplier gain exhibited a small but steady decrease due to the enhanced electron belt existing during 1962 and 1963. Since both an inflight calibration source and differential energy resolution were provided, this gain shift was accurately monitored.

Explorer XIV was launched on 2 October 1962 with geocentric apogee of 103,000 km, an initial perigee altitude of 270 km and a 36-hour orbital period. The initial angle between the line of apsides (the vector from the earth to the satellite at apogee) and the earth-sun vector was 70° and increasing with time. The active life extended from 2 October 1962 to 6 August 1963 except for a two week turn-off in January. For the present analysis only data taken above 73,000 km were used. The satellite at that time was in the transition, or magnetosheath, region between the magnetosphere and interplanetary space; nevertheless because

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of the rigidity of the particles under study, it is felt that the energetic particle measurements are representative of interplanetary conditions.

The counting rates of the detector are shown for two integral energy level of ~3 and ~6 MeV in Figure 1. Background and calibration counts have been subtracted. The dashed line indicates a fiducial mark each 27 days. The arrows indicate sudden commencements occurring during the course of an event. The most striking feature is the repeated occurrence of the proton increases within one day of the 27-day marker. The curves vary greatly in amplitude ranging from the very small event on 27 May, which is short and barely detectable, to the relatively large events of 10 February and 1 May. Data for solar rotations #1770 and 1779 are not shown but the observed counting rate suggests that a small event in July was definitely present at the appropriate time and that the December event was just above the threshold of detectability. Each recurrence event is immediately preceded by a period of complex magnetic activity. In each case except that of 9 March 1963 there is at least one sudden commencement followed by a magnetic storm, and in the March event there is a large magnetic storm. In each case the counting rate increases rapidly after the sudden commencement and displays a strong asymmetry with the initial increase and partial decay followed generally by a long plateau region. The absence of any intensity dependence on geocentric distance, the long persistence of the proton increase, and the further observations by the University of Chicago experiment on IMP-I at distances of up to 193,000 km clearly indicate these events cannot be produced by the interaction of the solar stream and the earth's magnetosphere.

Over the limited dynamic range available it is found that the energy measurements for the recurrent events are best ordered by exponential spectra of the form $I(\geq E) = I_o \exp(-E/E_o)$. The spectra for the maximum of each event are shown in Figure 2. The increase on 27 May is quite definite at all energies. In general, E_o does not vary markedly during the course of an event. For these low energies, an exponential kinetic energy spectrum is also equivalent to a power law spectrum in total energy of the form $I(\geq E) = k/(938 + E)^{\gamma}$ where E is the kinetic energy in MeV and $\gamma \approx 250$. The high energy data on 2 May with a flux of $\sim .1$ proton/cm^2-sec-ster >80 MeV does not fit either representation.

The continued presence of these protons is taken as evidence they are being continually accelerated by the sun. Whether this acceleration occurs near the surface of the sun or in interplanetary space at the turbulent interface between the faster moving plasma of the stream and the slower moving plasma of the quieter surrounding region cannot be decided in a definitive manner at the present time. As a working hypothesis we prefer the latter interpretation and believe the data tend to support this view. This process could be analogous to that postulated by Parker[5] for a blast wave propagating through interplanetary space. Dessler and Fejer[6] have also discussed the instabilities that might occur at such an interface. The efficient trapping of these particles is surprising when one notes the ease with which the flare-associated events can propagate from the sun. Three of these primary events on 15 and 24 April and 14 June are also shown in the data of Figure 1. As expected, these are characterized by well defined flares and/or Type IV radio emission. The late April and June primary events are probably the smallest ever recorded.

The solar stream containing the low-energy protons reported here has previously been extensively studied as a source of M-region disturbances extending from August, 1962 to early 1964.[7,8] The plasma associated with this stream was observed in deep space by Snyder[9] from September to December, 1962. He measured a marked enhancement of the plasma velocity associated with the passage of the stream. Several of the larger events noted here have also been observed by Van Allen _et al._ on Injun[10] and Masely _et al._ using polar riometers.[11] However, the Explorer XIV observations provided the first opportunity to undertake a systematic study with sufficient sensitivity to identify the particle species, to obtain energy spectra, and to make evident the long-term recurrent nature of these events.

The identification of the solar regions responsible for M-type disturbances has long been controversial. The two Explorer XII recurrence events in 1961 showed conclusively that the particle streams and initial M-type magnetic storms began within one day of central meridian passage of the parent region. This indicates a far greater lateral spread of the plasma stream than had been previously assumed. The 1963 events display a similar behavior. Our tentative identification of the appropriate solar region would be a continuation of that proposed by Snyder. Again, the anomalous short transit times can be accounted for in terms of the great lateral spread.

References

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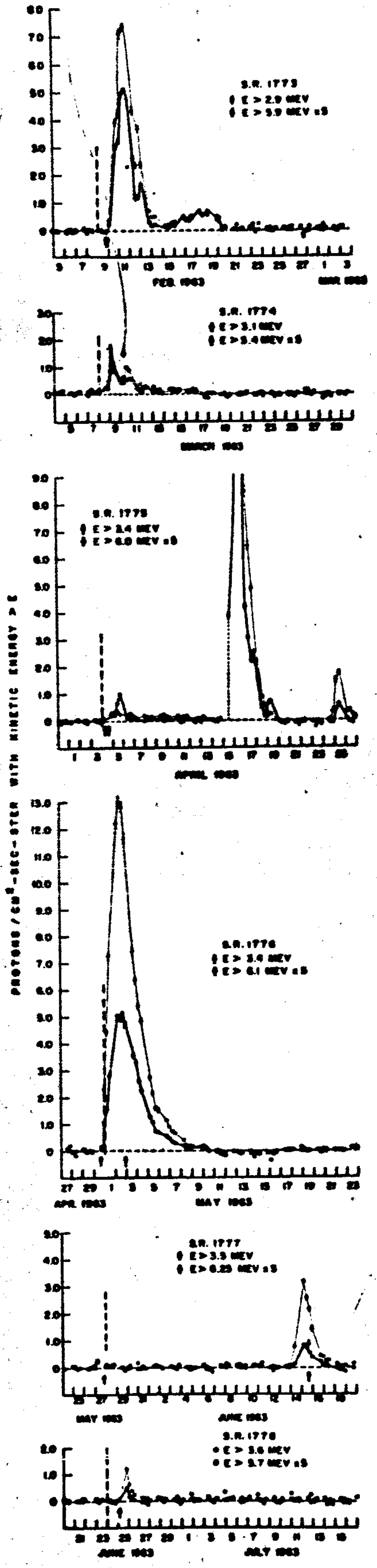
Figure Captions

1. Integral proton intensities for solar rotations 1773 to 1778. Each data point represents a six-hour average and, unless otherwise shown, errors are smaller than the data symbols. Only data taken above 73,000 km are used. The arrows indicate sudden commencements followed by magnetic storms and the dashed line is a 27-day fiducial marker. Three flare-associated events occur in late April and mid-June.

2. Integral energy spectra of the observed proton intensity increases. Data are shown for each event when the > 6 MeV component was at maximum intensity.



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FEB. 1963
S.R. 1774
MARCH 1963
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APRIL 1963
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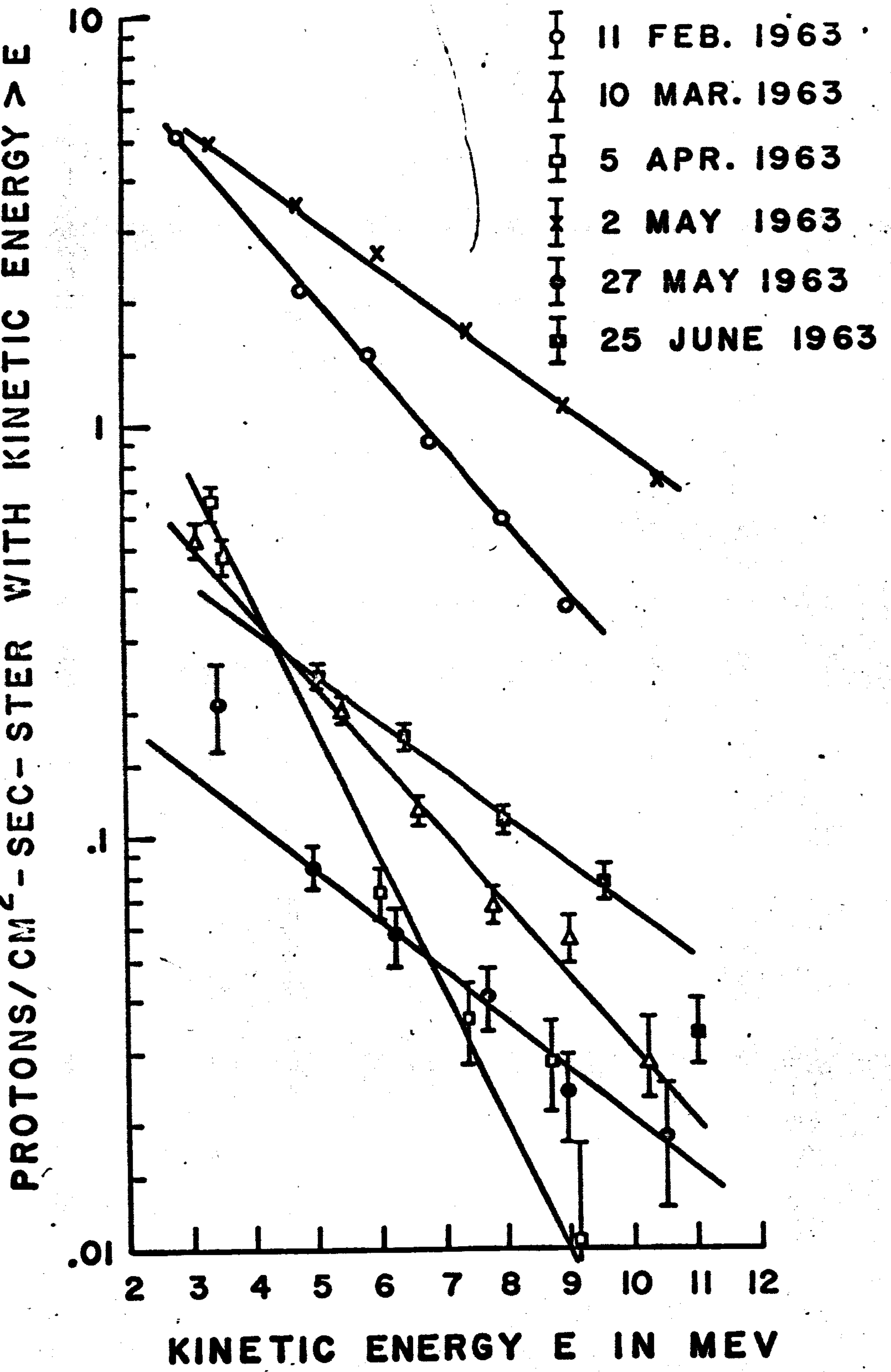

11 FEB. 1963
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5 APR. 1963
2 MAY 1963
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25 JUNE 1963
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