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The solar energetic particle event of April 14, 1994, as a probe of shock formation and particle acceleration

S. W. Kahler,[1] H. V. Cane,[2] H. S. Hudson,[3] V. G. Kurt,[4] Y. V. Gotselyuk,[4]
R. J. MacDowall,[5] and V. Bothmer[6]

Abstract. Gradual solar energetic particle (SEP) events observed at 1 AU are associated with coronal mass ejections (CME) that drive shocks which are presumed to accelerate the ions and electrons to suprathermal energies. However, high-energy (> 30 MeV) proton and (> 1 MeV) electron events are nearly always associated with both CMEs and flares, suggesting that the acceleration of those particles, particularly the electrons, could be attributed to the associated flares. Only one clear example of a high-energy SEP event without an active region flare association has been reported previously. We discuss a second such SEP event, on April 14, 1994, associated with a well-observed solar X ray arcade structure spanning $\sim$ 150° of solar longitude. The SEP event, observed by detectors on the IMP 8 and Koronas I spacecraft, began $\sim$ 10 hrs after the beginning of the X ray event and was temporally and spatially associated with the last of three weak interplanetary type III radio bursts observed by the Ulysses low-frequency radio experiment. The delayed onset and rapid rise of the SEP intensities preclude a recent interpretation in which SEPs were presumed to be accelerated by a shock driven by a CME which erupted at the onset of the X ray event. Yohkoh soft X ray subtracted images show a large-scale arcade brightening west of $\sim$ E10° beginning about 8 hours after the initial brightening near the east limb. We suggest that the April 14 SEP event at Earth was produced by a shock driven by a CME associated with the later brightening near central meridian. The initial X ray brightening may also have been associated with an earlier CME.

1. Introduction

Recent work has shown that the largest solar energetic particle (SEP) events, characterized by gradual intensity timescales, are produced in the corona and interplanetary medium by shocks driven by coronal mass ejections (CME) [*Cane et al.,* 1988; *Reames et al.,* 1996; *Kahler,* 1996]. Another class is the impulsive event, characterized by lower SEP intensities, higher electron/proton (e/p) values, enriched abundances of He^3 and high-Z elements [*Reames,* 1995], and associations with solar flares, in which ions are believed to be accelerated by waves produced by electron beams [*Roth and Temerin,* 1997].

Since most SEP events are also associated with flares, it is important to find cases of large, gradual SEP events without associated flares to confirm the shock source for gradual SEP events and to determine the characteristics of shock-accelerated particles. More than a dozen cases of few MeV ion events associated with solar filament eruptions but without flares were observed on ISEE 3 [*Cane et al.,* 1986b; *Sanahuja et al.,* 1991]. In those cases the SEP events were also associated with interplanetary shocks. The important role of CMEs in those events is implied by the CME associations with both filament eruptions and interplanetary shocks [*Kahler,* 1992]. However, for high-energy ($E > 50$ MeV) SEPs, only one event with an observed associated CME and filament eruption but no flare has been reported. That event occurred on December 5, 1981 [*Kahler et al.,* 1986].

While shock acceleration of ions appears on firm ground, the acceleration of energetic ($E > 100$ keV) electrons is not well understood. These electrons are commonly accelerated in flare impulsive phases, but their production in coronal or interplanetary shocks is un-

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[1] Air Force Research Laboratory, Hanscom AFB, Massachusetts.

[2] Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, Maryland.

[3] Solar Physics Research Corporation, Institute of Space and Astronautical Science, Sagamihara, Japan.

[4] Institute of Nuclear Physics, Moscow State University, Moscow, Russia.

[5] Laboratory for Extraterrestrial Physics, NASA Goddard Space Flight Center, Greenbelt, Maryland.

[6] Institut fur Reine und Angewandte Kernphysik, University of Kiel, Kiel, Germany.

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certain [*Kahler*, 1996]. *Kahler et al.* [1994] calculated the ratios of peak E > 70 keV interplanetary electron intensities to E > 55 keV hard X ray fluences from solar flares to determine the efficiencies with which solar nonrelativistic electrons escape the Sun. The idea was to look for a higher escape efficiency for electrons with associated CMEs and presumed shocks on the assumption that many of those electrons would be accelerated by the shock high in the corona, where the ambient density and resulting X ray bremsstrahlung are low. They found little difference between escape efficiencies of electron events with and without CMEs, suggesting no evidence for shock acceleration. However, the December 5, 1981, SEP event was characterized by significant fluxes of 0.2 < E < 2 MeV electrons and no detectible hard X ray event [*Kahler et al.*, 1994]. There are also a few cases of E > 70 keV electron events without detectable hard X ray bursts observed by the Venera 13 and 14 spacecraft [*Daibog et al.*, 1989]. Beyond 1 AU, electrons can be accelerated to relativistic energies in traveling shocks [*Lopate*, 1989] and to E > 50 keV in corotating shocks [*Roelof et al.*, 1997]. However, with little evidence for shock acceleration of electrons near the Sun, it would be useful to find any further cases of electron events with associated CMEs or interplanetary shocks but without associated flares.

If we have no associated flare or coronagraph observations, the SEPs from a coronal/interplanetary shock can give us some indication of the timing or position of the CME driving the shock [*Cane et al.*, 1988]. SEP observations indicate that strong shocks may extend up to 300° in longitude near the corona but at most 180° at 1 AU [*Cane*, 1996]. The observations of SEPs at 1 AU occur in dynamic situations in which field lines are convected past the Earth, resulting in a changing magnetic connection to progressively eastward solar regions [*Reames et al.*, 1996]. The SEP onset begins at the Earth soon after the outwardly propagating shock intersects the field line to the Earth and therefore serves as a limited probe of the shock propagation. However, it is clear that some shocks are not associated with the production of SEPs while others may result in SEP production over either extensive or limited ranges of distance from the Sun [*Kallenrode*, 1996]. Thus a major problem in SEP studies is to define the temporal and spatial distributions of SEP acceleration at shocks.

In section 2 we discuss a solar eruptive event which resulted in an E > 50 MeV ion and an E > 1 MeV electron event at the Earth. The absence of an associated active-region flare and the characteristics of the SEP event suggest that these SEPs were shock accelerated.

2. Observations

2.1. SEP Data

Two-hour averages of proton intensities from the IMP 8 spacecraft are shown in Figure 1. The SEP event began ~ 1200 UT on April 14 and shows clear velocity dispersion from the lowest (1 MeV) to the highest (50 MeV) energy ranges. The spectrum computed by taking the peak intensities in that range gives a power-law spectrum with an exponent of about -4.

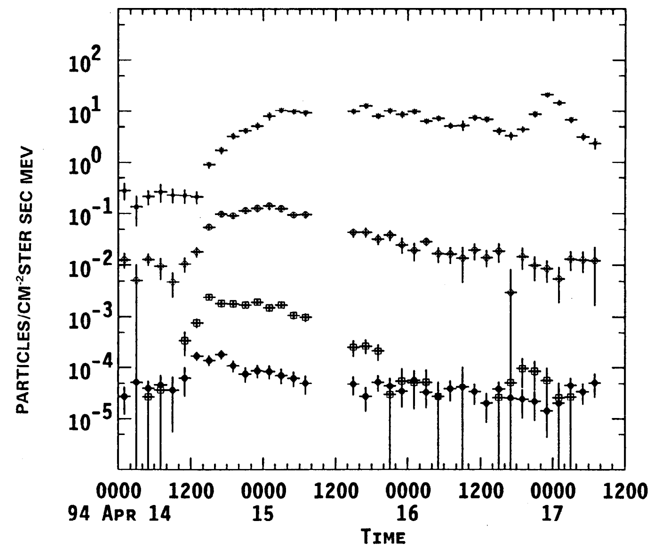

Figure 1. Two-hour IMP 8 proton intensity averages from April 14 through April 17, 1994. The energy ranges are: crosses, 0.88-1.15 MeV; open circles, 5.96-11.10 MeV; squares, 24.25-28.74 MeV; and solid circles, 42.93-63.20 MeV. The second peak in the ~ 1 MeV fluxes occurred at 2300 UT on April 16 at the time of an inferred interplanetary shock and geomagnetic sudden commencement.

The onset of the SEP event is shown in more detail in Figure 2. The IMP 30-min averages for protons (bottom) and the electron intensities observed with MKL detector on the Koronas I spacecraft (top) are shown. Both the IMP proton intensities and Koronas electron intensities indicate a rather sharp event onset at ~ 1200 UT. The solar particle detector complex, SKL, which includes the MKL detector, is described in detail in *Kuznetsov et al.* [1995], and their Figure 1 shows intensities from the SKL instruments over the period April 14-18. Because the Koronas I is in a low-altitude polar orbit, the intensities are averaged over each polar pass. The intensities are higher over the south polar passes as a result of the sunward pointing, negative-polarity interplanetary field, which provides a better magnetic connection to the geomagnetic south polar fields than to the north polar fields. A negative-polarity interplanetary field at the Earth is consistent with the calculated Stanford source surface magnetic field map.

A useful parameter characterizing a SEP event is the e/p ratio [*Cane et al.*, 1986a]. Since no electrons were measured in the IMP 4-19 MeV energy channel, we used the peak intensity of 0.4 e/cm^2 s sr MeV from the Koronas 0.5-1.3 MeV electron channel and calculated the e/p ratio of the 0.5-1.3 MeV electron and 9-23 MeV proton intensities. That ratio is 13, which is similar to

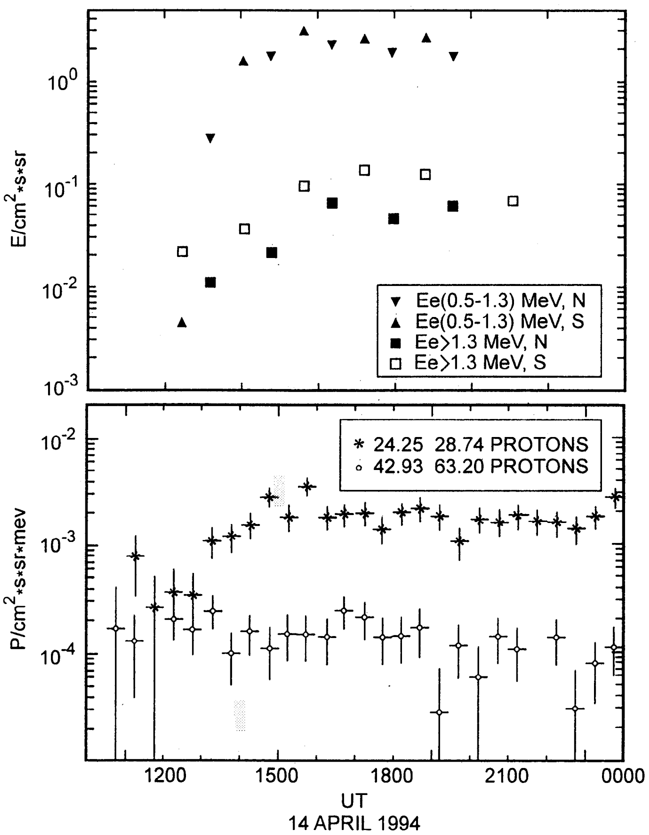

Figure 2. (top) Fluxes of two electron energy channels from the Koronas spacecraft. Each data point is averaged over a polar pass. Field lines from the sun were inward, or negative, polarity and connected to geomagnetic field lines at the south pole. Fluxes at those polar passes were therefore higher than fluxes at the north polar passes. (bottom) Thirty-minute flux averages of two proton energy ranges from IMP 8 showing the onset of the April 14 event.

the calculated equivalent values for IMP gradual SEP events. Since the impulsive events generally have values of hundreds or even thousands the ratio establishes the April 14 SEP event as a gradual event.

A SEP event was only very weakly observed from April 18-22 on the shoulder of a corotating interaction region event by the low-energy (1 to 3 MeV) telescope (LET) on the Ulysses spacecraft, located at a latitude of 60°S and a distance of 3.3 AU from the Sun and 35°E of the Earth [*Bothmer et al.*, 1995, 1996]. With an average solar wind speed of 800 km/s [*Bothmer et al.*, 1995], Ulysses was magnetically connected to a solar longitude of 50°W to 60°W. The SEP event at Ulysses was observed in conjunction with a CME and a forward and reverse shock pair [*Gosling et al.*, 1994] which were associated with the April 14 Soft X ray telescope (SXT) X ray event by *McAllister et al.* [1996] (hereafter McA96), *Lemen et al.* [1996], and *Dryer et al.* [1997]. The peak intensity was about 3 x 10^{-3} p/cm^2 s sr MeV [*Bothmer et al.*, 1996], more than 4 orders of magnitude less than the peak intensity at IMP 8 (Figure 1). This event was consistent with the general result that the high-latitude SEP events are orders of magnitude weaker than their counterparts observed in the ecliptic plane [*Bothmer et al.*, 1996].

2.2. Solar and Geomagnetic Observations

The April 14 SEP event occurred during a time of very low solar activity. The GOES 1-8 Å flux was below B level (10^{-7} W/m^2) for the 12 hours preceding the onset of the SEP event. The only reported Hα flare activity was a faint subflare at 09°N, 02°E at 0837 UT (Solar Geophysical Data, 1994). No fixed frequency or spectral radio bursts were reported on April 14 (Solar Geophysical Data, 1994).

The prominent solar activity during April 14 was a large soft X ray arcade event observed with the SXT and described in detail by McA96. Yohkoh images of the event development have been published by McA96, *Alexander et al.* [1996], and *Dryer et al.* [1997]. In Figure 3 we show selected pairs of Yohkoh direct and subtracted images of the event. The coronal arcade followed a long section of the southern polar crown magnetic neutral line, growing to a longitudinal extent of 150° and a latitudinal extent of 30° to 40°, as seen in the 1251 UT direct image of Figure 3. The first subtracted image shows that at 0246 UT the eastern end of the event was dominated by a bright loop with a cusp at the top, suggesting a twisted or reconnecting structure. However, the larger western portion of the brightening was dominated by a thin linear feature running along the magnetic neutral line from ~ 37°S, 30°E to 30°S, 15°W. Thin linear soft X ray features commonly occur during filament eruptions, apparently above the Hα filaments [*Kano*, 1994; *Watari et al.*, 1996]. In this case, however, no rising motion was detected. The two later subtracted images of Figure 3 show that as the eastern part of the arcade grew dimmer, the western part grew brighter. The boundary between the two distinct regions lay at ~ 10°E, near a kink in the magnetic inversion line. The two bright linear features evident in the subtracted images of 1050 and 1251 UT lie ~ 2.2 and 3.0 arc min south of the bright linear feature observed at 0246 UT. The observations of that region are consistent with an initial X ray enhancement associated with a very small Hα filament, followed by a large loop arcade structure with its bright top appearing in projection south of the magnetic neutral line. The appearance of two such bright features at the arcade top in the 1050 and 1251 UT images, however, is unusual.

This event did not show an obvious dimming signature that could have been associated with the depletion of the corona during formation of a CME. *Hudson* [1996] first noted this type of signature in the large arcade event observed at the limb by *Hiei et al.* [1993], resembling the event discussed here. As noted by *Hudson and Webb* [1997], dimming signatures observed by the Yohkoh SXT may include large-scale alterations of the

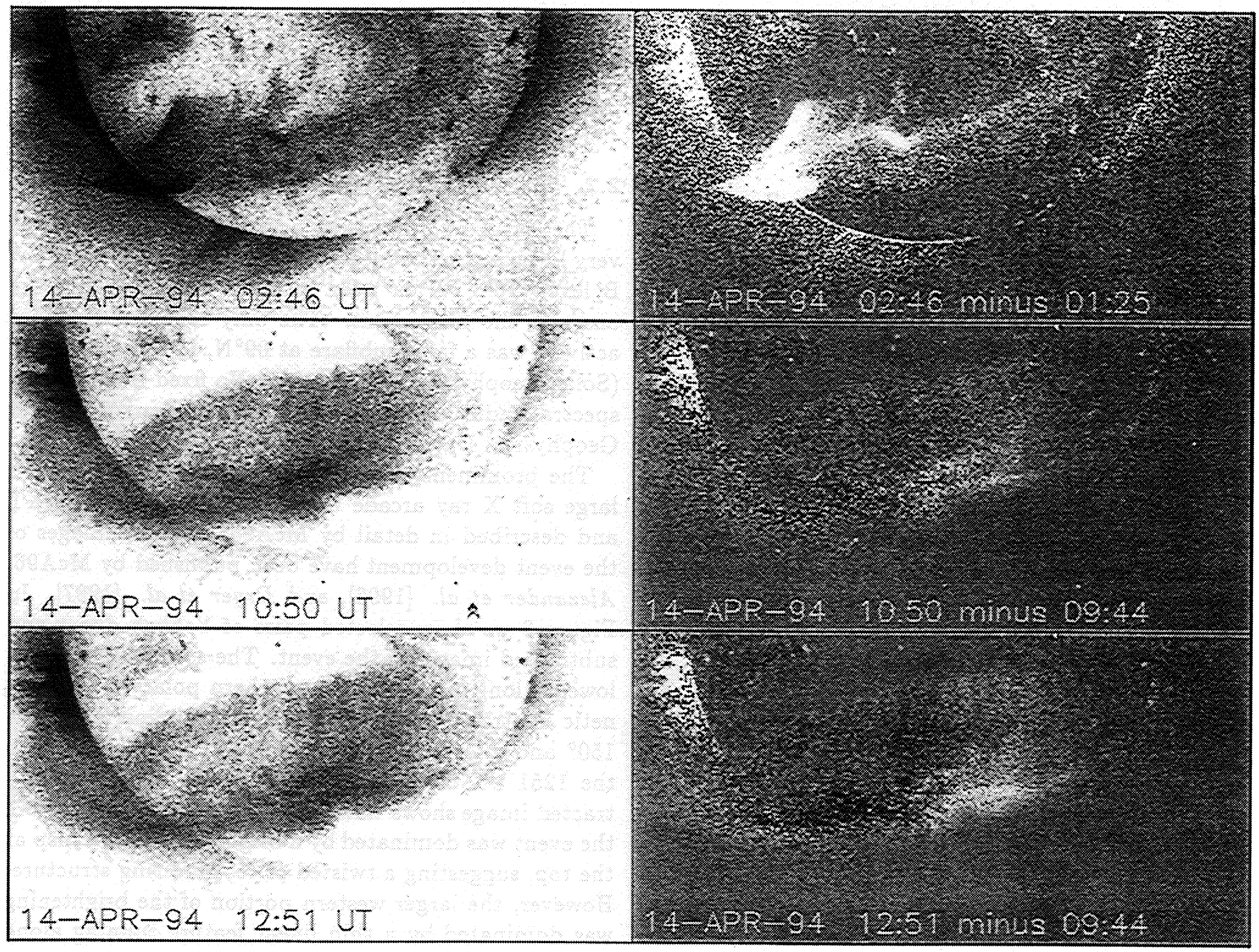

Figure 3. (left) Yohkoh soft X ray negative images showing the southern solar hemisphere during April 14, 1994. (right) Corresponding subtracted images with brightness increases shown in white and decreases in black. North is up. The 0246 UT subtracted image shows the loop and cusp characteristic of coronal arcades near the east limb and the faint linear feature characteristic of filament heating to the west. The images at 1050 and 1251 UT show the dimming of the eastern arcade loops (black) and brightening of the central meridian arcade loops (white).

configurations of the coronal holes. While restructuring of coronal hole boundaries clearly took place after the eruption [*Alexander et al.*, 1996], the early SXT images do not yield a dimming signature to indicate the source of the CME flow.

A large geomagnetic storm occurred on April 16-17. McA96 discussed the geomagnetic records to argue that the storm was initiated by a weak storm sudden commencement (SSC) which occurred at ~ 2015 UT on April 16 and that a shock was responsible for the SSC. The increase in the few-MeV intensities at IMP at ~ 2200 UT also supports that argument. In addition, there was a two-step decrease in the galactic cosmic ray intensity of ~ 4% at the Deep River neutron monitor consistent with the presence of a shock and associated ejecta [*Cane et al.*, 1996].

IMP interplanetary plasma and field data are available only until 1200 UT on April 14, after which no further data are available until April 19. The solar wind speed preceding the time of the SEP onset was ~ 700 km/s, implying a magnetic connection longitude of ~ 35°W. This places the Earth only ~ 10° to the west of the intersection of the solar source surface neutral line with the ecliptic. The magnetic field was inward pointing, showing that it was connected to the negative solar field south of the heliomagnetic equator.

2.3. Interplanetary Radio Observations

Observations of low-frequency (1.25 to 940 kHz) radio emission during April 14 were made with the Unified Radio and Plasma Wave (URAP) investigation on the Ulysses spacecraft. A summary of the URAP observations at high-heliographic latitudes was presented by *Stone et al.* [1995]. On April 14, Ulysses was at 30°E, 60°S at a distance of 3.2 AU from the Sun (shown schematically in Figure 12 of McA96).

An intensity plot of the URAP fluxes at selected frequencies is shown in Figure 4. On the basis of their highly circularly polarized signals and the results of a direction-finding program, we find that the small bursts at > 300 kHz are Jovian in origin. The most intense features at frequencies < 100 kHz are the fast-drift type III bursts labeled A, B, and C, which are solar in origin. The starting frequencies of these bursts are unusually low for type III bursts, with those of bursts A and B at 272 kHz and that of C at 148 kHz. In addition, a narrow-band solar feature observed from about 1300 to 1800 UT is probably the signature of an interplanetary type II burst.

Because the type II and type III bursts are weak, their two-sigma direction limits do not allow us to determine the solar longitudes of the burst source regions, but they do show a general shift of positions of the successive type III bursts from east to west and a type II burst source somewhat east of the Sun-Earth line. The direction-finding program assumes that the burst emission originates in the ecliptic plane. If we associate the relativistic electron onset at ~ 1200 UT with one of the type III bursts, then it is consistent only with burst C, which becomes significant in flux at ~ 1130 UT. The type III burst emission is due to electrons with velocities of v ≈ c/3, so the observed onset of event C at 148 kHz (at ~ 0.4 AU from the Sun, assuming harmonic emission) would have resulted from electron acceleration ~ 10 min earlier in the corona. The arrival of faster 2 MeV electrons from the same source would be expected to begin at or soon after 1130 UT, consistent with Figure 2.

3. Discussion

3.1. Interplanetary Shock and SEP Source Region

McA96 used Mauna Loa Observatory coronagraph data to argue that in the April 14 event a CME disrupted a helmet streamer underlying the heliospheric current sheet. They associated the CME with a shock detected at both the Earth and Ulysses. The probable interplanetary type II burst detected at about 1500 UT in the URAP data adds further support to that point of view. Assuming second harmonic plasma emission, the shock location at that time was east of the Sun-Earth line at a distance from the Sun of about 50 R_s, so a shock leaving the Sun 13 hours earlier at 0200 UT would have traveled with an average speed of ~ 750 km/s. Assuming deceleration in transit to the Earth, this speed

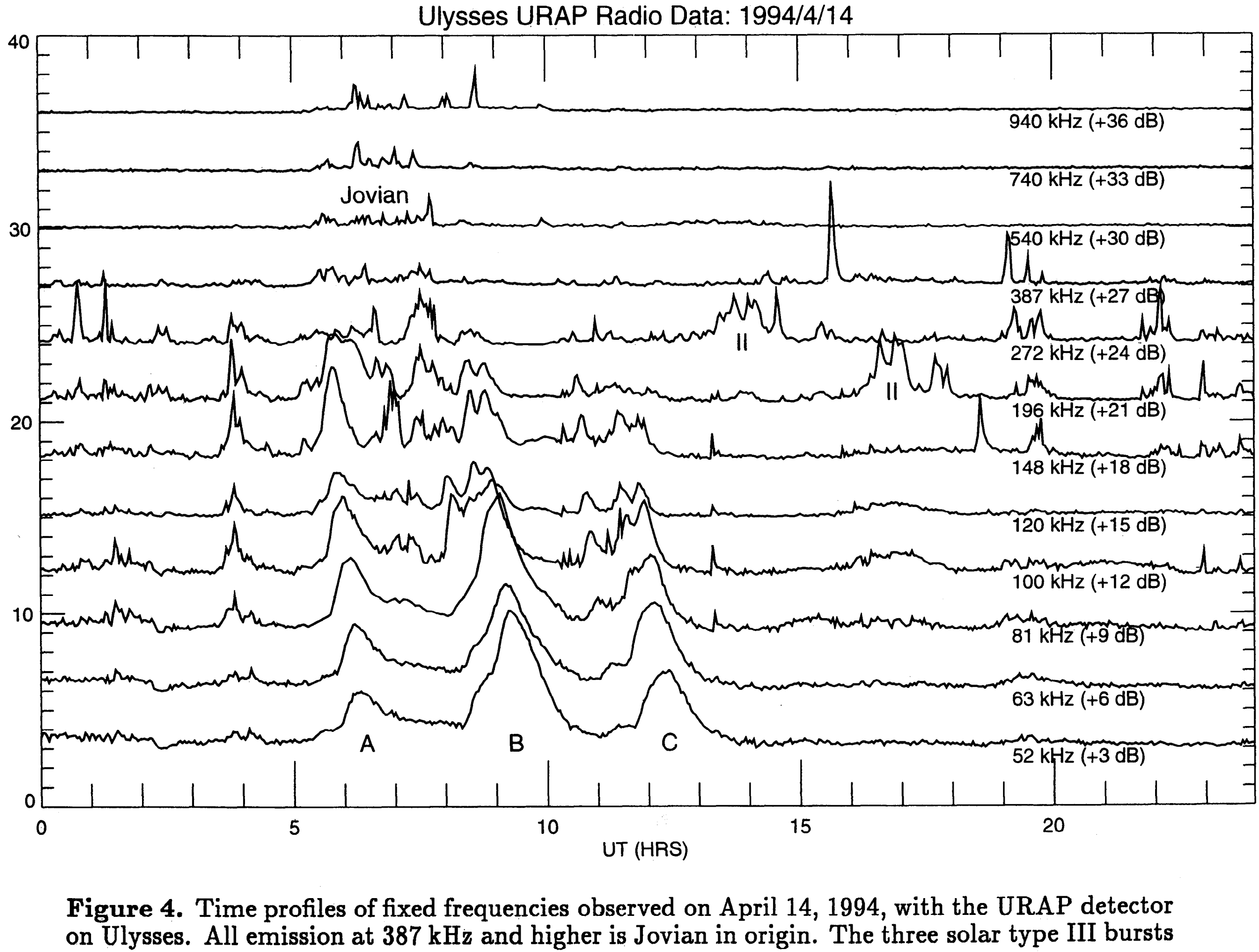

Figure 4. Time profiles of fixed frequencies observed on April 14, 1994, with the URAP detector on Ulysses. All emission at 387 kHz and higher is Jovian in origin. The three solar type III bursts are labeled A, B, and C, and the probable type II burst is labeled II.

is consistent with the average Sun-Earth shock transit speed of 630 km/s inferred from the SSC on April 20.

The SEP onset at the Earth occurred nearly 10 hours after the observation of the first soft X ray arcade loops. The Sun-Earth travel times of the relativistic electrons and 50 MeV protons in the SEP event are an hour or less, so this means that the SEP acceleration occurred nearly 10 hours after the observation of the first soft X ray postflare loops. Two scenarios for the unusual 10-hour delay were suggested by McA96. The first was that a shock formed quickly but had to propagate outward until intersecting the geoconnected field lines. However, delay times between associated Hα flare maxima and ~ 50 MeV SEP onsets are commonly ≤ 5 hours for flares located in the eastern hemisphere [*Cane*, 1996], and the rapid 10 to 12-hour rise of the April 14 SEP event from onset to maximum flux (Figure 2) suggests a source region west of ~ 20°E [see *Cane et al.*, 1988, Figure 8]. The onset delay and rapid rise profile therefore argue against this traditional interpretation for the SEP event.

The second scenario of McA96 was that the CME did not form a shock immediately. Assuming some shock deceleration in transit to the Earth [*Cane et al.*, 1986b], an average Sun-Earth speed of 630 km/s would imply a shock speed near the Sun of perhaps 1000 km/s, placing the shock formation at ~ 50 R_s. However, no evidence for such extensive delays in shock formation was found for those shocks associated with solar filament disappearances [*Cane et al.*, 1986b], so the April 14 shock considered by McA96 probably formed not long after the beginning of the X ray arcade at 0200 UT. Thus we believe that neither of these scenarios, which associate the SEP event with a shock driven by a source CME at 45°E beginning ~ 0200 UT, provides a good explanation of the observations.

The interplanetary type III burst labeled C in Figure 4 occurs at the appropriate time and position to be associated with the SEP event. Let us consider the broader context of this event. Except for the three bursts of Figure 4, the URAP observations show that this was a very quiet solar period, with no other interplanetary type III bursts from April 8 to 19. The simultaneous and successively westward movement of both the large X ray arcade formation and the type III burst locations suggest an obvious physical connection between the two. As discussed by *McA96* and shown in Figure 3, the arcade brightening along the X ray axis did not happen uniformly in time but rather involved successive appearances of elongated east-west structures accompanied by new sections of arcade loops.

We suggest that the April 14 SEP event was generated by a later CME-driven shock initiated near central meridian at ~ 1000 to 1200 UT, well after an initial CME, inferred from the probable interplanetary shock and X ray arcade structure to occur at 0200 UT. The later CME occurred at about the time of a major expansion of the large X ray arcade across the solar central meridian (McA96 and Figure 3). A later CME requires no delay in the shock formation or SEP onset and explains the rapid rise to maximum SEP flux, the inferred central meridian source for a weak shock, and the delayed westward development of the X ray arcade structure. It furthermore avoids the possible problem of explaining how one can get a CME width of 150°, inferred from the X ray longitudinal span, when plane-of-sky widths of white-light CMEs rarely exceed 100° [*Hundhausen*, 1993]. Multiple CMEs may obviate the need for a single magnetic structure to be observed at two widely separated points in space: at Ulysses (61°S, 30°E) and at the Earth [*Hudson et al.*, 1996].

Pairs of fast CMEs occurring < 10 hours apart, originating from adjacent regions of the corona, and associated with SEP events have been observed previously [*Kahler*, 1993]. *Cane et al.* [1991] have argued that in May 1979, a large filament erupted in two phases about 15 hours and 30° apart, leading to separate shocks and SEP events. As in those cases, the resulting configuration of the April 14 interplanetary shocks is not obvious. However, one possibility is that those shocks were narrowly directed in space [*Cane et al.*, 1986b] and maintained their separate identities, with the first shock toward the east detected at Ulysses and the second shock near central meridian detected at Earth. Another is that the two shocks eventually merged in space [*Whang*, 1984].

The basic picture of two separate CME/shock pairs suggested by the SEP, X ray, and radio data is contrary to the assumption of a single CME used in the MHD model of *Dryer et al.* [1997] for the April 14 event. Those authors used a density pulse lasting 7 hours and centered at central meridian and 45°S to model a single CME driving a shock observed both at Ulysses (as a forward and reverse shock pair) and at the Earth. Their model calculations began at 18 R_s with an assumed event onset at 1 R_s at 0200 UT. Despite the significant differences between their model assumption of a single broad CME starting at 0200 UT at central meridian and the implication from the data of two spatially and temporally widely separated CMEs for shock drivers, *Dryer et al.* [1997] find the errors in their predictions of shock arrival times at the Earth and at Ulysses to be < 8% and 4%, respectively. This good agreement appears to be due to their post hoc selection of model input parameters rather than to an accurate simulation of the interplanetary dynamics.

3.2. SEP event

The SEP event of April 14 is now the second well-documented case in which protons of 50 MeV and electrons of 1 MeV have been observed in association with an eruptive solar event lacking an active-region flare. This event and the previous event of December 5, 1981, were both associated with interplanetary shocks, which are the inferred sources of the energetic particles. Shock acceleration of ions to energies as high as 1 GeV now seems established [*Kahler*, 1994, 1996], but the case for relativistic electron acceleration at shocks has definitely been weaker [*Kahler et al.*, 1994]. The lack of any flares, hard X ray bursts, or metric type III bursts around the time of the April 14 SEP event establish a shock as the only plausible source of the 1 MeV electron event. It is surprising that more electron events clearly associated with shock acceleration have not been found earlier [*Kahler et al.*, 1994].

It is of interest to compare the April 14, 1994, solar event with that of the December 5, 1981, event. The December 5 solar event was observed in Hα as the disappearance of a large filament at $\sim$ 25°N, 40°W, followed by a double-ribbon brightening [*Kahler et al.*, 1986]. A fast ($v > 800$ km/s) CME was also observed with the Solwind coronagraph in spatial and temporal association with the erupting filament. Only a very small Hα filament was observed with the April 14 event, but the X ray arcade structure observed with the Yohkoh SXT left no doubt of a large-scale eruption along the polar crown neutral line (McA96). The December 5 CME was probably faster than that of April 14 and was located much closer to the magnetic field lines connecting to the Earth. In both events, no associated metric type II or type III burst was observed, but a weak kilometric burst signified an interplanetary shock in the December 5 event. We attribute the probable interplanetary type II burst of the April 14 event to an earlier eruptive event at 0200 UT.

The SEP event of December 5 was about an order of magnitude larger in peak intensity than that of April 14, but both events were characterized by rapid rises from onset to peak intensities of $\sim$ 10 to 12 hours at 30 MeV. Both events were also characterized by power-law distributions in energy with exponents of $\gamma \geq 4$, among the steepest values of the exponents for SEP event samples compiled by *van Hollebeke et al.* [1975] and by *Cane et al.* [1988]. *Kahler et al.* [1986] suggested that steep spectra were associated with the late formation of shocks as indicated by the absence of metric type II bursts. There are reasons to believe that the interplanetary shocks accelerating SEPs are not low-frequency extensions of metric type II bursts [*Vrsnak et al.*, 1995; Cane, 1997], but the April 14 SEP event is consistent with the suggestion that if the shock is weak or formed relatively late, then the SEP spectra are steeper than usual.

4. Conclusions

To establish observationally that CME-driven shocks can accelerate SEPs without associated effects of active-region flares, it is necessary to find SEP events associated with solar eruptive events but unaccompanied by active-region flares. The December 5, 1981, SEP event was associated with a filament eruption but no flare and has stood as the sole unambiguous case of shock acceleration of $E > 30$ MeV protons and $E > 1$ MeV electrons [*Kahler et al.*, 1986]. The April 14 SEP event now provides a second unambiguous case of shock acceleration of SEPs to these energies.

The SEP intensity time profile, the Yohkoh soft X ray images and the URAP radio observations support our view that the April 14, 1994, eruptive event occurred as at least two CMEs separated by 8-10 hours. The first CME probably produced the shock observed at Ulysses, and the second CME produced a shock and the SEP event observed by IMP and Koronas at Earth. This result is inconsistent with the recent model calculations of *Dryer et al.* [1997].

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V. Bothmer, Institut fur Reine und Angewandte Kernphysik, University of Kiel, 24118 Kiel, Germany. (e-mail: bothmer@estec.esa.nl)

H.V. Cane, Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771. (e-mail: cane@ncf.gsfc.nasa.gov)

Y.V. Gotselyuk, and V.G. Kurt, Institute of Nuclear Physics, Moscow State University, Moscow 119899, Russia. (e-mail: juvg@srdlan.npi.msu.su; vgk@srdlan.npi.msu.su)

H.S. Hudson, Solar Physics Research Corp., ISAS, 3-1-1 Yoshinodai, Sagamihara-shi, Kanagawa-ken, Japan 229. (e-mail: hudson@isass1.solar.isas.ac.jp)

S.W. Kahler, AFRL/VSBS, 29 Randolph Road., Hanscom AFB, MA 01731-3010. (e-mail: kahler@plh.af.mil)

R.J. MacDowall, Laboratory for Extraterrestrial Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771. (e-mail: xrrjm@leprjm.gsfc.nasa.gov)

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