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THE IDENTIFICATION OF SOLAR ^{3}He-RICH EVENTS AND THE STUDY OF PARTICLE ACCELERATION AT THE SUN

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ABSTRACT

We use kilometric radio observations to associate type III radio bursts with solar ^{3}He-rich events and to identify and study the sources of those events at the Sun and the transport of the particles outward toward Earth. The events exhibit an impulsive behavior that earns them a natural role in the event classification scheme based upon the time scale of the particle acceleration process. Multiple ^{3}He-rich events are observed frequently from a single active region where they provide a convenient signature to test theories of particle storage and transport. These multiple events act as impulsive probes of the condition of the interplanetary medium. Their profiles contrast with the source-acceleration–induced profiles of the long-duration events from the same active region that are interspersed among them.

Subject headings: cosmic rays: general — particle acceleration — Sun: radio radiation

I. INTRODUCTION

Over the past year a confluence of radio, X-ray, γ-ray and particle observations has led to substantial gains in our understanding of the relationship between particles observed in space and their acceleration at the Sun. The classic two-phase acceleration model proposed by Wild, Smerd, and Weiss (1963) and the two classes of X-ray events found by Pallavicini, Serio, and Vaiana (1977) have been related by Cane, McGuire, and von Rosenvinge (1986) to describe two separate classes of particle events distinguished by the time scale of their soft-X-ray emission. The two classes are found to have distinctly different signatures, not only in their source properties but also in the abundances (Cane, McGuire, and von Rosenvinge 1985, 1986) and spectra (Evenson *et al.* 1985) of the particles observed in interplanetary space.

Class I or impulsive events have short-duration (tens of minutes or less) X-ray profiles arising from compact source regions relatively low in the corona (Pallavicini, Serio, and Vaiana 1977). Energy for particle acceleration in these events probably comes from magnetic field line reconnection in areas of newly emerging flux (Vlahos *et al.* 1986). The events are characterized by type III and type V radio bursts generated by electrons. This dominance of electrons is seen in the inteplanetary population of energetic particles, where it is better described as a paucity of protons (Cane, McGuire, and von Rosenvinge 1985, 1986; Evenson *et al.* 1985). The most typical class I events may be the small nonrelativistic electron events that generate the type III radio bursts (Lin 1974) and have recently been related to ^{3}He-rich events (Reames, von Rosenvinge, and Lin 1985; Reames and Lin 1985) that are the subject of the present study. Gamma-ray events are also observed to be impulsive in nature, requiring substantial nucleonic acceleration at the Sun but with enhanced electron/proton abundance ratios in space (Chupp 1984; Evenson *et al.* 1984).

Class II events have long-duration ($\sim$ hours) X-ray profiles with the X-rays arising from extended regions high in the corona (Pallavicini, Serio, and Vaiana 1977). These long-duration events (LDEs) produce coronal mass ejections (CMEs), generate coronal and interplanetary shocks, and exhibit type II and type IV radio emission (Svestka and Fritzova-Svestkova 1974; Sheeley *et al.* 1983; Cane and Stone 1984; Cane 1985; Sheeley *et al.* 1985; Cliver *et al.* 1985). The LDE X-ray profile may be the result of field-line reconnection in the high corona after the relatively slow but extensive disruption of the coronal fields by the CME (Anzer and Pneuman 1982). Most of the large proton events are associated with long-duration phenomena (Nonast, Armstrong, and Kohl 1982; Kahler *et al.* 1984; Cane, McGuire, and von Rosenvinge 1986) with the bulk of the particle acceleration presumed to occur at the coronal shock. Class II events are sometimes, but not always (Kahler *et al.* 1986), preceded by an impulsive phase with the radio properties of class I events.

The ^{3}He-rich events (whose general properties have been reviewed by Ramaty *et al.* 1980 and by Kocharov and Kocharov 1984) have recently been shown to be clearly impulsive in nature. Reames, von Rosenvinge, and Lin (1985, hereafter RvL) used the association between ^{3}He and electrons to determine the solar sources of the events and found metric type III emission from them. These events have extremely impulsive X-ray profiles. Kahler *et al.* (1985*b*) showed an absence of type II emission and coronal mass ejections, except possibly for a few events with substantial proton abundances where the class II mechanism might also be present. In contrast, the large class II events show $^3\mathrm{He}/^4\mathrm{He} < 2.6 \times 10^{-3}$ (Mewaldt, Spalding, and Stone 1984), a limit that is consistent with the solar wind value of $(4.9 \pm 0.5) \times 10^{-4}$ (Coplan *et al.* 1984).

Kahler *et al.* (1985*a*) examined the coronal source regions for the 12 ^{3}He/electron events identified in RvL. They found the events to be well correlated with kilometric type III radio bursts which are excited by solar electrons streaming outward through interplanetary space but found a poorer correlation with phenomena deeper in the solar atmosphere, especially with Hα brightenings. These events, like the small impulsive electron events generally (Kane *et al.* 1974), seem to originate relatively high in the corona (in contrast to the larger impulsive events observed by Pallavicini, Serio, and Vaiana 1977). Furthermore, radio emission may be a more sensitive indicator of event classes and mechanisms than the weaker soft X-ray profiles.

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Meanwhile Reames and Lin (1985) examined all of the electron events in a 9 month period (153 events) for the presence of ^{3}He. They found that over half of the events had detectable levels of ^{3}He and, of the larger events in the period that had measurable intensities of 20 keV electrons (86 events), two-thirds were accompanied by ^{3}He. While these associations are less definitive than those of RvL, they strengthen the likelihood that ^{3}He would be seen in all impulsive electron events given slightly more sensitive detectors. Are the anomalously enhanced ^{3}He/^{4}He ratios, in fact, a property of the acceleration mechanism responsible for all class I events?

To address this question and to further explore the properties of the ^{3}He acceleration source, it is essential to increase the number of identified source regions for ^{3}He-rich events. It is also of special interest to study some of the largest ^{3}He-rich events, most of which occur after the 15 month period that was accessible to the RvL study. In this paper we further establish the relationship between the kilometric type III radio bursts and the ^{3}He-rich events and then use those data to identify and study ^{3}He-rich event sources during the period from 1978 August through 1982 August.

II. OBSERVATIONS

a) Instrumentation

Both the particle and the radio observations reported in this paper were made aboard the *ISEE 3* spacecraft while it was located in a halo orbit about the libration point, 240 Earth radii in the sunward direction from Earth.

Helium isotope measurements were made with the Very Low Energy Telescope (VLET) on the Medium-Energy Cosmic-Ray Experiment described by von Rosenvinge *et al.* (1978). Typical isotope resolution of the instrument is shown in RvL. Electron measurements were made using the High-Energy Telescope (HET) on the same experiment.

Kilometric radio data used to study the interplanetary type III radio bursts were obtained with the Radio Mapping Experiment on *ISEE 3* described by Knoll *et al.* (1978). This experiment uses a 90 m dipole antenna in the spin plane and a 15 m antenna along the spin axis to track radio emission in the 30 kHz to 2 MHz region corresponding to solar radial distances of >1 AU to ~ 6 solar radii, respectively. The type III bursts, caused by excitation of the local plasma by 5–100 keV electrons streaming outward along the interplanetary magnetic field (IMF) lines, can be tracked with this experiment to locate the source at the Sun within about 10° in longitude or less.

b) Event Selection and Association

In order to find candidate ^{3}He-rich events for this study, the VLET data were scanned for well-defined helium increases within the ^{3}He-rich time periods defined previously (Kahler *et al.* 1985*b*). Events found by RvL were excluded from this study. Dynamic radio spectra were examined during the candidate time periods for associated type III bursts and single-frequency time histories were used to improve the source timing for identified events. Further properties of these events were then found in *Solar Geophysical Data.*

The time evolution of a series of events on 1982 August 13–14 is shown in Figure 1. Particle conditions were quiet before 2030 UT on August 13; the VLET recorded only five ^{4}He particles and no ^{3}He in the 6 hr period early in Figure 1, and the electron intensity remained at background level (data gaps are best seen as white areas in the radio spectra, but all data are affected). Three prominent type III bursts beginning at August 13 2302 UT and August 14 0241 UT and 0509 UT may be seen in the dynamic spectra, with corresponding increases occurring almost immediately in the energetic electron intensities at *ISEE 3*. Corresponding increases in the 2.2–3.4 and the 1.3–1.6 MeV amu^{-1} He intensities are seen about 2 and 3 hr, respectively, after the electron onsets. This timing agrees well with that expected from velocity dispersion as found by RvL and is the same for each of the events in this sequence. The onset of the lowest energy He from the 0509 UT event falls in the data gap; however, elevated intensities at the lower ^{3}He/^{4}He ratio from this event were seen shortly after 1200 UT (not shown).

The radio and electron onsets for the first prominent ^{3}He-rich event in Figure 1 are obscured by the data gap from 1800–2000 UT. However, a metric type III event beginning at 1813 UT listed in *Solar Geophysical Data* is a likely source, since its timing agrees well with that of the later three events. The presence of a kilometric type III event in the data gap is strongly suggested by the low-frequency emission seen after the gap at 2000 UT.

Detailed plots of single-frequency time histories are appended at the bottom of Figure 1 for two of the type III bursts. The radial distance from the Sun in solar radii corresponding to each frequency is shown in the figure based upon the *Helios* model of the interplanetary plasma density (Bougeret, King, and Schwenn 1984).

Figure 2 shows the particle and radio data for the 1982 June 25 period. In the figure there are two large isolated events in a low-level He background from unidentified sources. The type III events begin at 0533 UT and 1945 UT. The first event shows an He onset but no energetic electrons, while the second event shows an electron increase, but the He onset is obscured by a data gap.

More complete associations for these events and for those in other time periods are shown in Table 1. This list includes most of the large, well-defined events of the 4 year period. However, this list should not be considered exhaustive; there are many small ^{3}He-rich events that have more poorly defined onsets and are hence more difficult to associate. Errors on the ^{3}He/^{4}He ratios in Table 1 include uncertainty in the background from earlier events (that affects only ^{4}He). Because of this uncertainty, this ratio is shown as a lower limit in four of the events and has a large error in three other events. Ratios are also corrected for an approximately 6% spill of ^{4}He into neighboring ^{3}He because of the instrument resolution.

Metric radio data and Hα flare properties of the events in Table 1 were found in *Solar Geophysical Data.* Soft X-ray profiles for many of these events (and those in RvL) may also be found in *Solar Geophysical Data.* These profiles are of short duration, and they occur within minutes (see RvL) of the type III emission. Owing to the weak X-ray emission in many events, we have chosen to concentrate on the more sensitive radio data in understanding these events.

c) Trajectories

Measuring the direction to the centroid of the radio emission region and using the *Helios* model of the interplanetary plasma density (Bougeret, King, and Schwenn 1984) to relate emission frequency with radial distance, it is possible to plot trajectories that track the electron population as it moves outward along the interplanetary field lines. Figure 3 shows such a trajectory, out to 1 AU, for the type III radio event of

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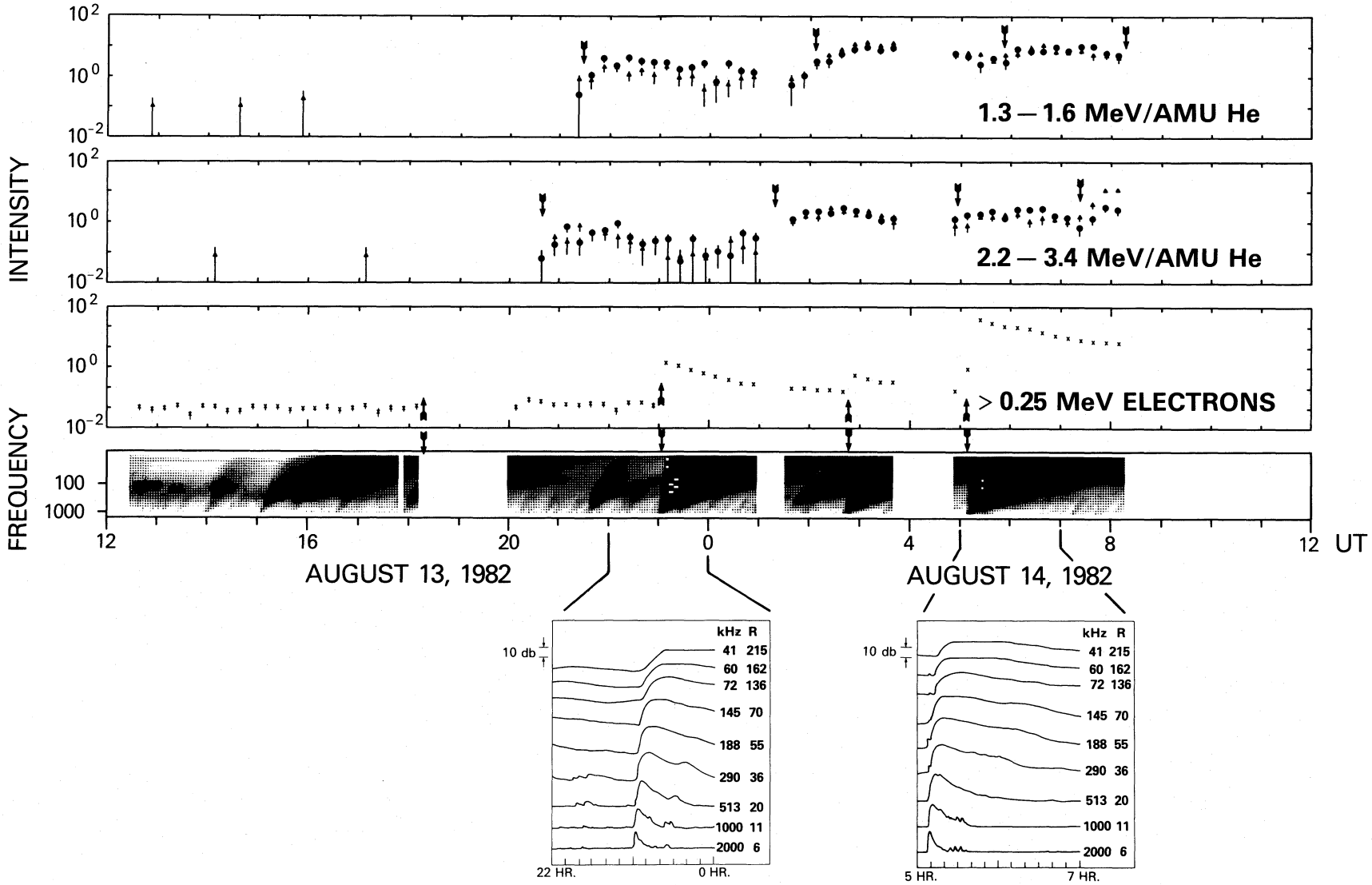

FIG. 1.—Time histories of ^{3}He (*circles*), ^{4}He (*triangles*) and electrons (*crosses*) with the dynamic radio spectra for the 1982 August 13–14 period. Arrows indicate the times of significant events. The spacing of the arrows is the same in all panels, but their position is shifted to allow for propagation delay. Single-frequency plots for the two largest events are appended at the bottom, with the distance from the Sun in solar radii shown for each frequency.

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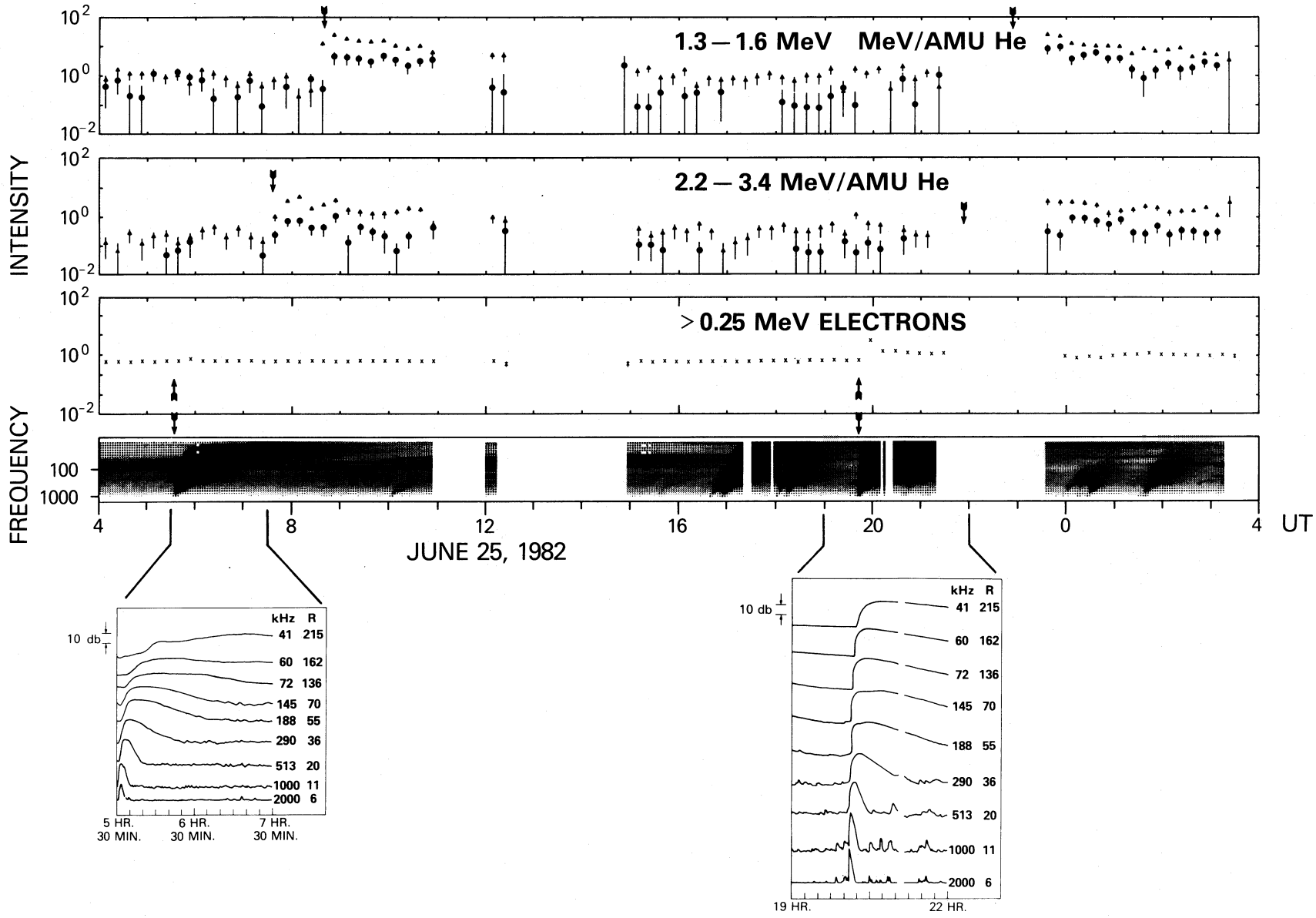

FIG. 2.—Particle and radio data for 1982 June 25–26 (see Fig. 1)

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TABLE 1

TYPE III AND FLARE ASSOCIATIONS OF ^{3}He-RICH EVENTS

DATE	1.3–1.6 MeV amu^{-1} He Onset	1.3–1.6 MeV amu^{-1} He Ratio	2 MHz TIME	METRIC TIME	TYPE	FLARE TIME	SITE	IMPORTANCE	REGION
				^{3}He-rich Events					
1979 Dec 14	2000	1.5 ± 0.1	1552–1605	1550–1555	2GG	1553–1643	N10W51	1B	16490
1979 Dec 23	~2100	1.9 ± 0.2	1726–1735						
1980 Nov 9	1930	$0.9^{+0.8}_{-0.2}$	1621	1620–1623	3G	1621–1633	S14W44	−N	17246
1980 Nov 10	0000	$3.7^{+1.8}_{-0.5}$	2035	2033–2035	2G, V	2028–2054	S12W48	−N	17246
1980 Nov 10	0830	4^{+3}_{-2}	0448	0448–0449	2G, V	0446–0508	S09W51	−N	17246
1980 Nov 10	1100	>4	0750	0747–0751	2G	0744–0749	S09W51	−N	17246
1980 Nov 11	1915	0.3 ± 0.1	Gap	1605–1614	2GG	1515–1715	N10W65	1B	17244
1980 Nov 15	1300	>1.6	1020	1018–1025	1G[a]	0953–1033	S12W44	−N	17255
1980 Dec 16	1830	0.5 ± 0.1	1455	1452–1458	3GG, V	1427–1511	N07E13	1B	17331
1981 Sep 15	2315	1.2 ± 0.2	1935	1933–1937	3GG, V				
1981 Nov 20	1330	0.2 ± 0.1	1045	1041–1043	2GG	ambiguous			
1982 Mar 10	1615	>2.2	Gap	1220–1255	3GG	1205–1302	S06W31	1N	3635
1982 Mar 10	2300	0.7 ± 0.2	1845	1844–1850	3GG, V	1845–1902	S06W34	1B	3635
1982 Jun 25	0830	0.24 ± 0.04	0533–0536	0530–0535	3S, IS	0528–0607	N14W50	−B	3781
1982 Jun 25	2330	0.36 ± 0.08	1945	1944–1945	3GG, V	1941–2002	N17W56	2B	3781
1982 Jun 30	1315	>1.4	0915						
1982 Aug 13	2130	1.9 ± 0.3	Gap	1813–1820	2GG				
1982 Aug 14	0200	0.8 ± 0.1	2302	2259–2303	3G, V	2257–2322	N11W59	−N	3837
1982 Aug 14	0600	1.2 ± 0.1	0241–0245	0238–0244	2G, V	0237–0310	N11W60	−B	3837
1982 Aug 14	0800	0.24 ± 0.05	0509	0506–0515	3G, V, II	0507–0525[b]	N11W62	1B	3837
				Related Events					
1980 Nov 10	~1600	<0.06	1140	1139–1158	3GG, V, II, IV[a]	1140–1321	S10W54	2B	17246
1980 Nov 11	2200	<0.05	Gap	1742–1753	3GG, V, II, IV	1729–1823	S11W69	2B	17246

[a] Decimetric.
[b] Gamma-ray event.

1982 August 14 0241–0254 UT (2 MHz occurrence time). The measured angle of the event subtended at the Sun at 1 MHz is 57° west, in good agreement with the associated flare longitude of 60° west. For this event the flare and *ISEE 3* appear to be well connected.

Figure 4 shows the trajectory, out to 0.6 AU, of the type III event of 1979 December 14 at 1550–1555 UT (2 MHz occurrence time). This radio burst is associated with a flare at N10W60. Figure 4*a* shows a three-dimensional trajectory of the event, out to 0.6 AU, and Figure 4*b* is a projection of the trajectory onto the ecliptic plane. The dotted curve is an idealized trajectory for a solar wind speed of 400 km s^{-1} and a footpoint located at 51° west. Extrapolation to 1 AU brings this trajectory close to *ISEE 3*.

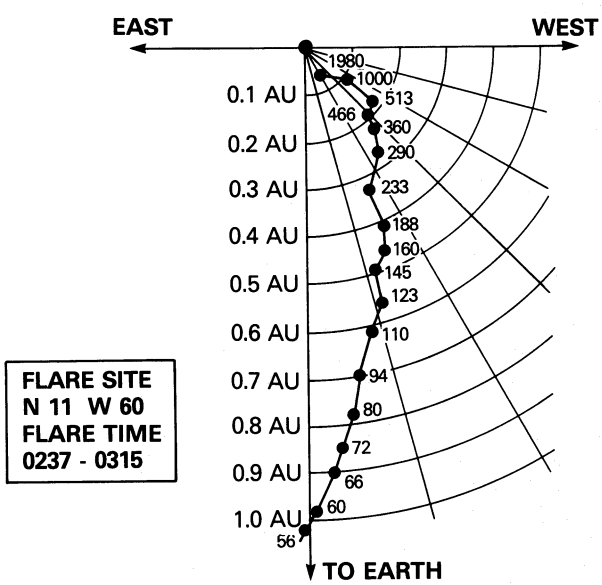

FIG. 3.—Type III trajectory for the event of 1982 August 14 0241–0245 UT (2 MHz time) out to 1 AU. The trajectory at 1 MHz (0.1 AU) subtends an angle at the Sun of 57°, in good agreement with the associated flare at N11W60.

The trajectory in Figure 4 serves to illustrate the relatively long, meandering path followed by particles from some events that departs considerably from the ideal Parker spiral. Different path lengths cause differences in the particle propagation times that cause variations in the onsets and peaking times from event to event, quite apart from differences in scattering along these paths.

The event of 1980 December 16 illustrates one of the problems encountered in attempting to determine the field lines connecting the source region with the observer. This type III radio event is composed of a large burst and a small burst. The latter is observable over a few midfrequencies only and otherwise merges into the larger burst. An associated Hα flare is located at N07E13. Can the particles from an eastern flare such as this find their way to the spacecraft? The trajectories for this event are shown in Figure 5. The *A* trajectory, determined from the large burst, appears to start from the east, jog strongly to the west, and then spiral off to the east. Particles following this trajectory would not reach *ISEE 3*. The small burst provides only a few points resulting in trajectory *B* to the west. Recalling that the radio experiment measures only the centroid of the emission, one cannot uniquely determine how or if these two trajectories are connected. It is not clear whether trajectories *A* and *B* were produced by two separate events or by a single event that injected particles onto widely separated field lines. It

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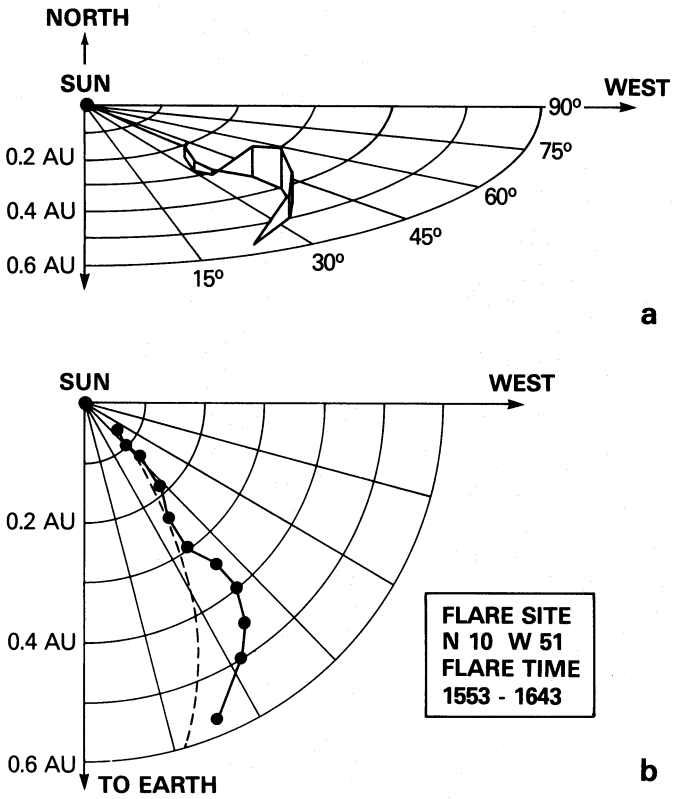

FIG. 4.—Trajectory of the type III radio burst of 1979 December 14 1550–1555 UT (2 MHz time) associated with the flare at N10W51. (*a*) The three-dimensional trajectory out to 0.6 AU. (*b*) The projection of the trajectory onto the ecliptic. The dashed curve is the idealized trajectory for a flare at W51 and a solar wind speed of 400 km s^{-1}.

is important to determine the extent to which particles from eastern flares can find their way onto field lines that connect with the vicinity of Earth.

d) *The 1980 November Events*

The series of events on 1980 November 8–11 provide an interesting study of a single active region with respect to the

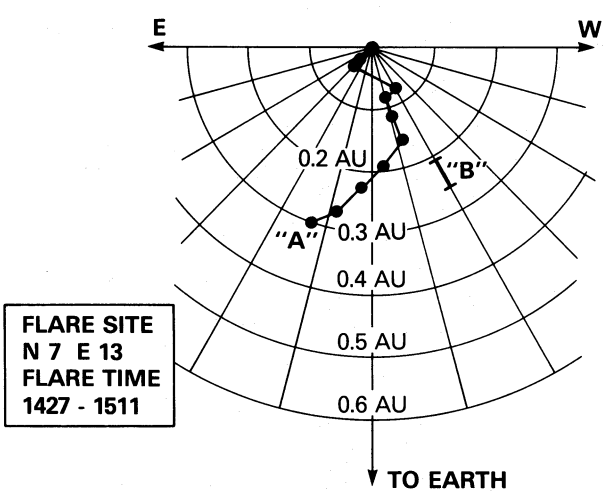

FIG. 5.—Complex type III burst of 1980 December 16 occurring between 1427 and 1511 UT (at 2 MHz), apparently associated with a flare at N07E13. The eastern (*A*) trajectory is the main radio burst, but a small event, seen in the same time interval at only a few frequencies, produces the western (*B*) branch.

efficiency of particle escape, their angular extent in space, and the mixture of class I and class II events from a single region. In Figure 6 the time histories of the 1.3–1.6 MeV amu^{-1} He isotopes are shown separately to highlight the contributions of different flares to each. At the top of the figure, rectangles show the onset and duration of all Hα flares listed in *Solar Geophysical Data* in McMath region 17246, the region that was found to contribute the prominent ^{3}He-rich events of the period. Only two of the flares are labeled with their importance, 2B, since the remainder are all subflares. For each flare, associated metric type III classifications are shown to identify flares with escaping electrons, and events with strong kilometric bursts are flagged (*triangles*) to show their continuation outward. Finally the time scale of the flare and radio events is shifted by 3.25 hr to compensate for the He propagation time and align the particles and their source.

Several striking associations are seen in Figure 6. The four ^{3}He-rich events in this period listed in Table 1, and, possibly, one other smaller event, align well with the corresponding flares with radio emission. The two large ^{4}He increases align with the two large 2B flares with the type II and type IV bursts (the first event at 1140 UT also has a CME; Kahler *et al.* 1984). There is almost a complete separation between the class I events that accelerate ^{3}He and the class II events that accelerate ^{4}He (and, of course, protons that are not shown) in this sequence.

Figure 7 shows the angular distributions in the arrival directions of He particles during the impulsive, ^{3}He-rich event at 0000–0100 UT on 1980 November 10 and the long-duration class II event at 1400–2000 UT on the same day. The similarity of the angular distributions and the persistence of the outward flow in a single hemisphere during the second event shows that the difference in event duration is not caused by interplanetary propagation but by differences in acceleration at the source.

III. RESULTS AND DISCUSSION

b) *The Association*

A most basic result of this study is the excellent association of the kilometric type III bursts with each of the ^{3}He-rich events. A few of the ^{3}He-rich events could not be associated because of data gaps or multiple bursts, but no events were found to lack type III bursts otherwise. This confirms the finding of Kaler *et al.* (1985*a*) for the events identified by RvL.

It is not surprising, of course, to see type III events without particles, owing to the much wider longitude coverage of the radio data. Lower sensitivity of the particle measurements might also be a factor; the events identified tended to have strong radio emission that propagated rapidly to low frequencies, suggesting the presence of abundant higher energy electrons.

b) *Propagation*

The timing of the events in Table 1 supports the picture, found by RvL, of relatively scatter-free propagation of the particles from the acceleration site to Earth. Many of the events have very fast onsets, reaching maxima within the first hour of observation as in Figure 2 and in the time histories shown by RvL and by Reames and von Rosenvinge (1983); they also show anisotropic field-aligned distributions in their direction of arrival. In the 33 events identified to date there is no evidence of any unexplained delay or other feature in the profiles that would require the existence of a process of coronal diffu-

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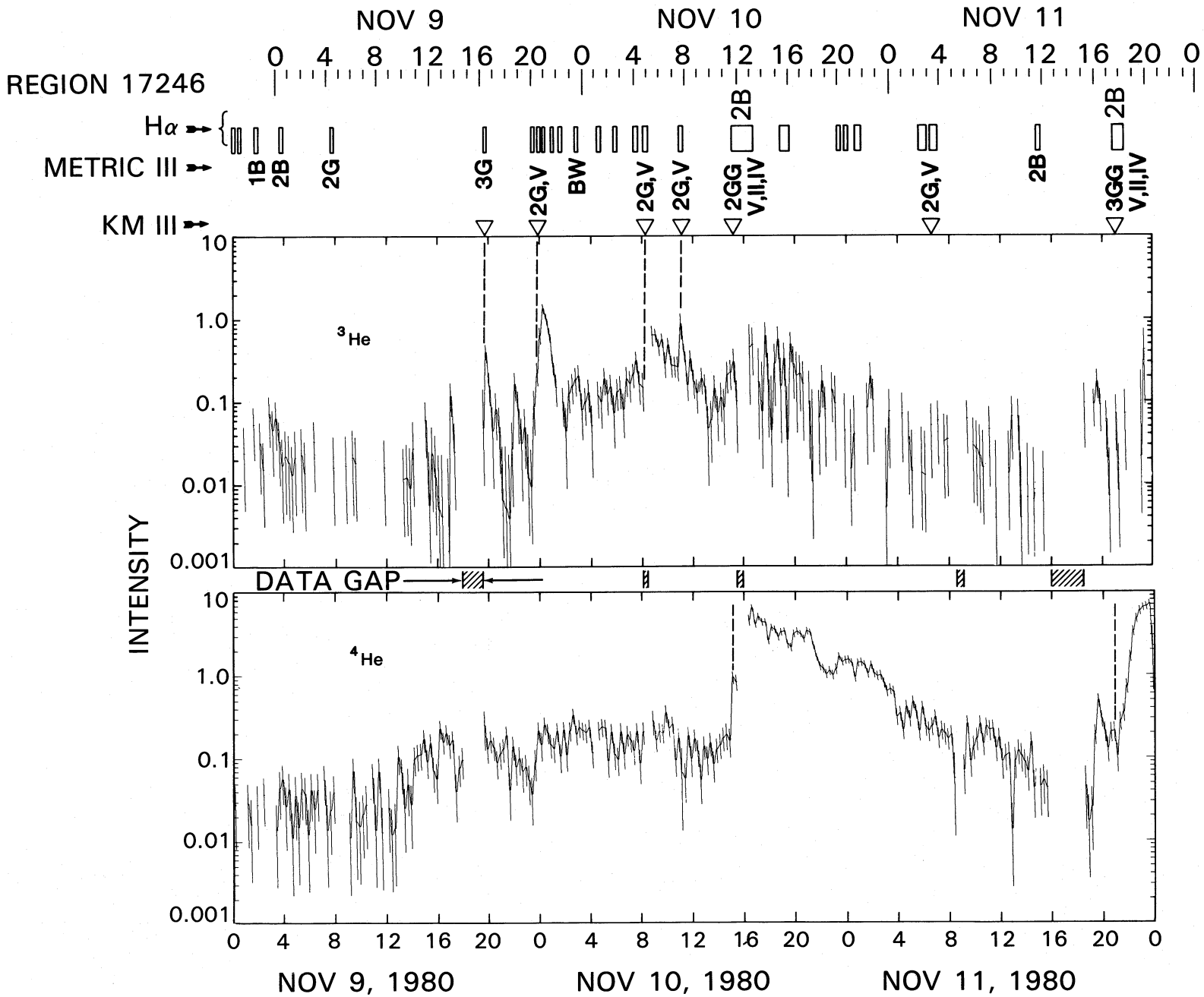

FIG. 6.—Time histories of ^{3}He and ^{4}He of 1.3–1.6 MeV amu^{-1} are shown in the two lower panels for the 1980 November 9–11 period. Above are shown the times of all flares from region 17246 and the metric and kilometric radio emission from each of the flares. Upper and lower time scales are shifted by 3.25 hr to allow for propagation times, so as to align the particle increases with their source flares.

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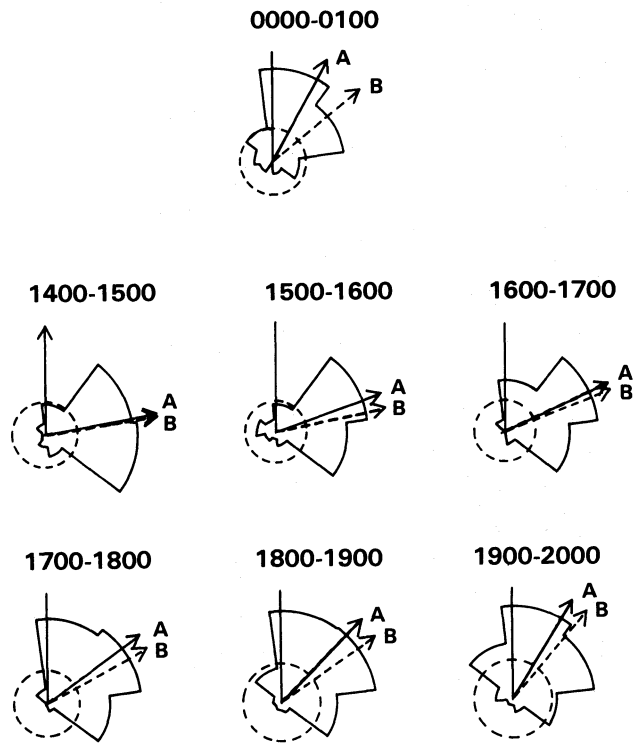

FIG. 7.—Angular distributions in the arrival direction of He during the two event periods at 0000–0100 and 1400–2000 on 1980 November 10. Vectors ***A*** and ***B*** show the mean anisotropy and magnetic field directions, respectively, during each hourly interval, and the solar direction is upward. Similar field-aligned flows characterize both events despite their differences in composition and duration.

sion or detainment to impede the particles as they leave the source region. Furthermore, since the events with different profiles (Fig. 6) and similar arrival distributions (Fig. 7) come from the same active region, we find it difficult to believe that the same region of the corona plays a diffusive role in forming the vastly different profiles.

The ^{3}He profiles of the events range from the extremely impulsive profiles of the 1980 November events in Figure 6 to the relatively smooth ones of the 1982 August events in Figure 1. The similarity of the profiles in a sequence of impulsive events (even those from different active regions) over a period of days suggests that these profiles are determined primarily by the condition of the interplanetary field through which all of the particles pass, rather than the local coronal region near a given source. This is seen clearly in the case of the 1980 November 11 1915 UT event in Figure 6, which has an impulsive profile like those of the series of impulsive events occurring much earlier but comes from a different active region.

In contrast to the 1980 November events, the profiles of the 1982 August events in Figure 1 show greater interplanetary scattering that affects both the He and the relativistic electrons for all of the events in the interval. The profiles can be understood as an equilibrium between scattering and focusing in the diverging field to determine the mean pitch angle; the larger the mean pitch angle with the field, the longer the mean spiral trajectory and the greater the delay of the intensity maximum.

The role of the equilibrium between scattering and focusing in determining the particle profiles was first considered theoretically by Roelof (1969) and further explored in considerable detail by Earl (1976*a*, *b*). Measured event profiles were fitted to this theory by Ma Sung and Earl (1978). While the latter authors saw profiles of individual events similar to all of those in Figure 6, the new feature here is that events with substantially different profiles come from the same active region within hours of each other and arrive with similar angular distributions (Fig. 7) that change little with time. Thus, we have been led to conclude that the long-duration particle profiles of class II events truly reflect a long period of particle acceleration at the source.

c) *Coronal Storage?*

The concept of the storage of energetic particles in coronal loops (Elliot 1973; Hudson 1985) is sometimes invoked to provide a seed population for later stages of acceleration and for subsequent events from the same active region (McDonald and Van Hollebeke 1985). Models for the enhancement of ^{3}He (Fisk 1978; Varvoglis and Papadopoulos 1983; Kocharov and Kocharov 1984) generally require a two-stage acceleration process in which ^{3}He is resonantly heated in the first stage and the high-energy tail of the thermal distributions is preferentially accelerated in the second phase. It might be tempting to assume that a heated population with enhanced ^{3}He could be stored in the corona and sampled in each of the multiple events from an active region. The list of identified ^{3}He-rich events includes seven groups of events in which the members of a group occur in the same active region. The ^{3}He/^{4}He ratio appears to vary randomly from event to event within a group, indicating a lack of support for a simple model of coronal storage in these active regions.

A further example of this reasoning is shown in Figure 6. If the series of ^{3}He-rich events on November 9–10 were to populate the high corona with stored particles, why are these particles not available as a seed population for shock acceleration in the large class II event at 1140 UT? This event has ^{3}He/^{4}He < 0.05 with all of the apparent ^{3}He signal in Figure 6 consistent with incomplete correction for the isotope resolution of the instrument. This large shock event seems to have no significant access to the population of energetic ^{3}He particles that was accelerated only a few hours earlier. If particles are stored in the corona at all, we would conclude that they are stored for times that are shorter than hours or at energies well below 1 MeV amu^{-1}.

In contrast to the variability seen in the ^{3}He/^{4}He ratio, Mason *et al.* (1986) find commonality in the abundances of C through Fe in all of the ^{3}He-rich events with only modest variations from one event group to the next. This could be taken as evidence that the material sampled by all of the events tends to come from the same temperature regime and, perhaps, the same coronal altitude (Kahler *et al.* 1985*a*). In addition, the observed charge states on the elements in these events (Klecker *et al.* 1984; Luhn *et al.* 1985) are higher, on the average, than in large solar events, suggesting a higher temperature source region with a temperature of 5×10^6 K.

d) *Gamma-Ray Events*

The event at 0507 UT on 1982 August 14 listed in Table 1 differs from the others in two respects. Both γ-ray emission (Kane *et al.* 1985) and type II radio emission were observed from the event. The presence of some ^{3}He has been observed at higher energies in two other large γ-ray events by Van Hollebeke, McDonald, and Trainor (1985). Although the isotope ratios of 0.02 and 0.03 found by those authors are well below those accessible to the VLET at low energies, there is still growing evidence that the γ-ray and ^{3}He-rich event types are not exclusive.

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The ^{3}He events with γ-rays are larger than those without, and they are accompanied by type II bursts, as are many of the larger impulsive events listed by Cane, McGuire, and von Rosenvinge (1986). However, attempts to make a systematic study of particle composition in γ-ray events are frustrated by selection biases in those events apparently caused by beaming of photons produced by electron bremsstahlung (Dermer and Ramaty 1986). The bias of identified γ-ray events toward the solar limb and the need for well-connected events for particle observations combine to reduce drastically the number of events available for study.

e) *Event Classes*

The ^{3}He-rich events studied here tend to have smaller electron fluxes than the large electron events studied by Cane, McGuire, and von Rosenvinge (1986). As noted previously, they also have shorter duration X-ray flares and a lower probability of type II bursts. We would associate the observation of type II bursts with the class II acceleration mechanism even though Cane, McGuire, and von Rosenvinge (1986) were unable to do so. If it is proper to understand the two event classes in terms of two different acceleration mechanisms, then it might not be surprising to find a contribution from both mechanisms to be present with greater probability in larger events.

The observation of both impulsive and long-duration events from the same active region in Figure 6 illustrates the clear contrast in the particle profiles of the event classes that are distinguished by their X-ray profiles. Here it is clear that these differences noted by Cane, McGuire, and von Rosenvinge (1986) do not arise from different interplanetary propagation conditions as discussed above but rather come from the physics of the acceleration process at the source.

It seems likely that the extended profile of the class II particle events is the result of an acceleration process that is itself extended in time, such as that of the propagation of a coronal shock that contracts the observer's bundle of field lines continuously as it moves outward into material of decreasing density. A related picture has been proposed on different grounds by Mason, Gloeckler, and Hovestadt (1984) to explain the uncorrelated fluctuations in element abundances seen during an event in terms of different samples of material encountered by an expanding coronal shock.

f) *Flare Associations*

The poor association between Hα flares and particles in space, excluding effects of IMF connection from the source to the Earth, can be seen in Figure 6. Only a small percentage of the flares from region 1746 show the metric type III signature of escaping electrons, and not all of those show kilometric type III. The events with kilometric type III do show ^{3}He increases from this well-connected region. This poor association viewed from the flares outward is also seen, to a lesser extent, in following particle events backward toward the flare (Kahler *et al.* 1985*a*).

Flares that are inefficient producers of interplanetary particles probably result from acceleration events that are low in the solar atmosphere or in magnetically closed regions, while impulsive particle events without flares come from events that are higher in the corona with little particle penetration down into the chromosphere.

g) *Longitude Distribution and Angular Size*

The identified ^{3}He-rich events with Hα flare coordinates define a sample of 15 active regions whose solar longitude distribution may be examined. This distribution has a median near 50° west longitude and a width of perhaps 40°. This width measures mainly the random motion of the interplanetary field connection longitude from variations in the solar wind speed. Wide variation in the connection longitude would be expected from trajectories such as that shown in Figure 4.

A measure of the angular extent of the particle population in space is given by the length of time during which ^{3}He-rich events from a given region are seen. Three regions contribute particles for 10–12 hr and one for almost 16 hr, implying angular widths of 5°–10°. This smaller width presumably reflects the spread of the particle distributions for fixed interplanetary conditions, while the 40° width found above includes variations in the IMF configuration.

IV. SUMMARY AND CONCLUSIONS

Kilometric type III radio emission can be used, in lieu of direct electron measurements, to identify the sources of solar ^{3}He-rich events, and a list of identified events has been presented. The list has been limited to larger events with well-defined onset times and is by no means exhaustive.

In comparison with larger class I electron events, the ^{3}He-rich events are extremely impulsive. Not only do they have fast X-ray profiles, but, during times of quiet interplanetary conditions, they exhibit some of the fastest particle profiles seen for solar ions. The events are rarely associated with type II bursts, and, when they are, they have a greater proton component (Kahler *et al.* 1985*b*). The ^{3}He-rich events must clearly be viewed as proton-poor (rather than electron-rich), since they have low p/He ratios as well as low p/e ratios. Furthermore, the ^{3}He-rich events, like the small electron events with which they associate, appear to come from higher in the corona than the class I events studied by Pallavicini, Serio, and Vaiana (1977). We suggest that low coronal height found by the latter authors may be a property of the larger, brighter events that they were able to observe and is not a property of all impulsive events that should belong to class I.

These impulsive ^{3}He-rich events frequently occur in sequences from a single active region that may also give rise to long-duration, class II events with extended intensity profiles that contrast sharply with those of the class I events. These different profiles strongly support different underlying acceleration mechanisms as the basis of the two classes. The ^{3}He-rich events within a sequence from the same active region show no obvious trend or persistence in the isotope ratio from event to event.

The kilometric and metric radio emission in the events is usually strong, with the occurrence of event groups in all of the identified metric sources and type V emission in about half of them. About half of the Hα associations are subflares, and half have importance 1B or 2B. Only a small fraction of observed Hα flares emit particles into space.

Several instances of ^{3}He enhancement in γ-ray events have emerged. This association is not surprising considering the impulsive nature of these events, but the presence of coronal shocks late in many of these events may obscure the association by adding a population of particles with no ^{3}He enhancement. No definitive relationship may be established with the small sample of events now available.

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