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MULTISPACECRAFT OBSERVATIONS OF SOLAR ^{3}He-RICH EVENTS

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ABSTRACT

We report on a systematic search of He isotope observations on the *Helios 1* and *2* spacecraft during the occurrence of 66 ^{3}He-rich time periods observed on *ISEE 3* over a 4 yr interval. Seven time periods show possible event associations but only three show confirmed events with similar ^{3}He/^{4}He ratios on *Helios* and *ISEE 3*. We use kilometric radio observations of type III bursts produced by electrons associated with the ^{3}He-rich events to map the interplanetary field lines outward from the events. The observations are best explained in terms of a narrow cone of emission of the particles from these events.

Subject headings: Sun: flares — Sun: particle emission — Sun: radio radiation

1. INTRODUCTION

Once regarded as a rare curiosity, solar ^{3}He-rich events are now described as a signature of the selective heating of the solar plasma by wave-particle interactions in the impulsive solar flares that are an everyday occurrence on the Sun (see review by Reames 1990). In the measurements of energetic ions near 1 AU, values of ^{3}He/^{4}He are observed that are often three or four orders of magnitude larger than the corresponding ^{3}He/^{4}He ratios observed in the solar atmosphere or in the ambient solar wind. ^{3}He-rich events are strongly associated with electron events (Reames, von Rosenvinge, & Lin 1985) and with type III radio radio bursts produced by electrons streaming outward from the Sun (Reames & Stone 1986; Reames et al. 1988). Abundances of heavy elements are also systematically enhanced in these events (see Mason et al. 1986).

It is generally believed that the particles accelerated in impulsive flares are confined to a relatively narrow cone of magnetic field lines as they propagate outward from the flare. This belief is inferred from the longitude distribution of the flares producing electron (Lin 1974), ^{3}He-rich (Reames et al. 1988), and Fe-rich (Reames, Cane, & von Rosenvinge 1990) events observed at Earth. These flares are observed to come from a limited region on the western hemisphere of the Sun which is magnetically well-connected to the observer. The flares themselves are quite compact (Kahler et al. 1985; see also Pallavicini, Serio, & Vaiana 1977) so it might not be surprising to find that particles emerge in a narrow cone of emission.

For flares that produce particles seen at Earth, the distribution of solar longitudes is only a rough measure of the average cone of emission of the particles. The magnetic field lines that pass near Earth have been observed to emerge from the Sun over a wide region of longitude from near central meridian to the west limb. Thus, a flare may be well connected to Earth over an extended longitude interval, called the "fast propagation region," simply because of variations in the connection longitude of the field from event to event. To measure the width of the cone of particle emission in a single flare, we must separate the measurements in space rather than time.

Observations of ^{3}He-rich events have not been confined to near-Earth spacecraft. Measurements of the events on the *Helios 1* and *2* spacecraft were reported over a decade ago by Hempe et al. (1979, see also Kunow et al. 1991). These authors measured ^{3}He/^{4}He ratios in several events and were able to compare observations from the two spacecraft during three events that occurred late in 1977. A more recent study of particle transport in ^{3}He-rich events was reported by Mason et al. (1989). The authors compared *Helios 1* and *ISEE 3* observations in one event in order to understand the effect of scatter-free transport on the time profiles and angular distributions, but no comparison of ^{3}He/^{4}He ratios were made. Other single-spacecraft *Helios* measurements of ^{3}He/^{4}He ratios in large γ-ray–line flares have been reported (Van Hollebeke, McDonald, & Meyer 1990).

Despite more than a decade of overlapping observations by instruments capable of resolving He isotopes on *Helios, IMP, ISEE, Pioneer, and Voyager* spacecraft, we can find only four examples in the literature, of ^{3}He-rich events that are observed on two spatially separated spacecraft. The event periods with multispacecraft comparisons are those of 1977 October 28, December 6/7, and December 26/27, described by Hempe et al. (1979), and that of 1979 May 17, studied by Mason et al. (1989).

In the present paper, we report the results of a systematic search of the *Helios 1* and *2* data for ^{3}He-rich events corresponding to those in the 66 ^{3}He-rich time periods reported (Kahler et al. 1985) from *ISEE 3* observations during the 1978–1982 time span. We compare ^{3}He/^{4}He for the events seen on more than one spacecraft, and we show the longitude separation of the spacecraft and their location with respect to the interplanetary (IP) magnetic field line from the flare for those events.

2. INSTRUMENTATION

Energetic particle measurements used to obtain the list of ^{3}He-rich events were made by the Medium-Energy Cosmic-Ray Experiment (von Rosenvinge et al. 1978) on *ISEE 3*. During the study period, the spacecraft remained in orbit

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about the L_1 Lagrangian point, 240 Earth radii upstream of Earth on the Sunward side. Typical resolution of the experiment for low-energy He isotopes has been shown by Reames, von Rosenvinge, & Lin (1985). A comprehensive scan for ^{3}He-rich events during the first 4 yr of the *ISEE 3* observations produced a list (Kahler et al. 1985) of 66 ^{3}He-rich time periods between 1978 August 15 and 1982 July 10.

For each ^{3}He-rich time period observed on *ISEE 3*, we searched data from the Kiel Experiments (Kunow et al. 1977) on the *Helios 1* and *Helios 2* spacecraft. The *Helios* spacecraft are in solar orbit with a perihelion of 0.3 AU and aphelion of 0.98 AU. *Helios 1* observations were generally available for the entire study period but *Helios 2* observations are available only up to 1980 March 8.

Since the degree of magnetic connection between the flare and the observing spacecraft is a central issue in this study, we have used kilometric radio data from the Radio Mapping Experiment (Knoll et al. 1978) on *ISEE 3* to map field lines from the flare site. This experiment determines the direction to the centroid of the radio-emitting electron population that produces a kilometric type III burst as it propagates outward along the field lines from the flare. Since the frequency of the radio emission depends upon the local plasma density, which decreases with distance from the Sun, it is possible to model the distance of the electron cloud from the Sun as a decreasing power-law function of the emission frequency (see Bougeret, King, & Schwenn 1984; Reiner & Stone 1988).

3. STATISTICAL CONSIDERATIONS

As stated above, we began with a list (Kahler et al. 1985) of 66 ^{3}He-rich periods observed on *ISEE-3*. In 56 of the 66 periods, at least one of the two *Helios* instruments was operative. During these periods we examined pulse-height data above 4 MeV amu^{-1} for evidence of any increase in ^{3}He/^{4}He. In addition, we examined time profiles of the rates of 0.3–0.8 MeV electrons, 4–13 MeV protons, and 4–13 MeV amu^{-1} He for any evidence of increases that might correspond to events that were also on *ISEE 3*. The seven candidate time periods listed as A–G in Figure 1 were identified as containing events that appear to match. Of the seven time periods, three (times A, B, and F) contain events that match in profiles and ^{3}He/^{4}He ratios, two (C and D) contain profiles that appear to correspond but the events are not ^{3}He-rich on *Helios*, and two (E and G) contain profiles that correspond, but a comparison of ^{3}He/^{4}He is not possible.

Before comparing the events that are observed on multiple spacecraft, we first consider the relationship between those that were and those that were not found. A priori, one of the most obvious reasons for a large "hit" to "miss" ratio is the possibility of a large spatial separation of the spacecraft. To compare spacecraft with different radial and azimuthal separations, we calculate the coronal footpoint longitude of a spacecraft using the measured solar wind speed at the time of the event and using the method of Nolte & Roelof (1973). The distribution of this longitude for *Helios* during each of the *ISEE 3* ^{3}He-rich periods is shown in Figure 1. Times of the "hit" periods are listed in the figure; it is not surprising that these cluster near 50° W longitude. Note, however, that the overall distribution of time periods is far from uniform. *Helios 1* has an unusually small probability of being near 50° W during the times of interest, while *Helios 2* has a larger-than-expected chance of that occurrence. Roughly 80% of the well-

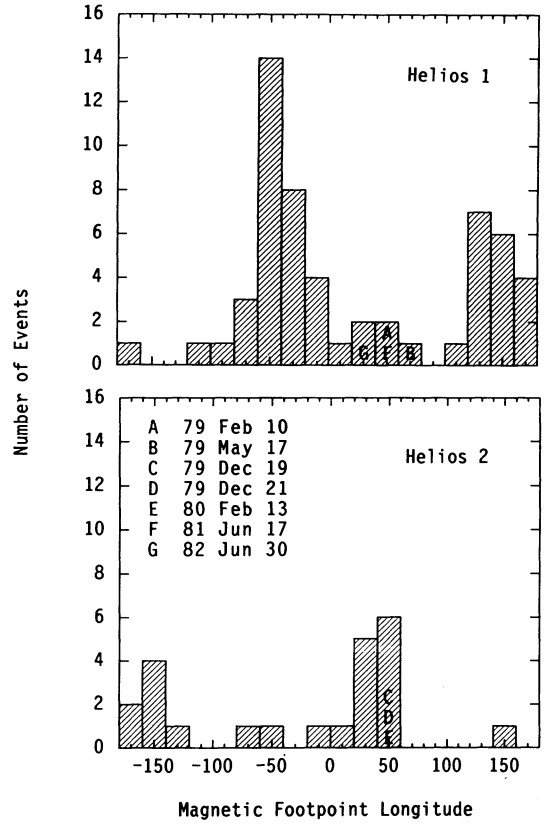

FIG. 1.—Distributions of solar longitude of the footpoint of the magnetic field line from the *Helios* spacecraft during each of the ^{3}He-rich periods seen on *ISEE* 3. Periods with possible corresponding events on *Helios* are listed and are identified in the histograms.

connected event for *Helios 1* result in "hits," while less than 30% of those for *Helios 2* result in hits.

Event size or intensity is another factor that can affect visibility. The 66 *ISEE 3* ^{3}He-rich periods (Kahler et al. 1985) range in fluence from ~200–33,000 (cm^2 sr MeV/amu)$^{-1}$ with a median fluence of ~1500. Of the seven candidate ^{3}He-rich periods found on *Helios*, four have larger than the median fluence (1600, 2300, 4100, and 5100 (cm^2 sr MeV/amu)$^{-1}$], and three have smaller [220, 390, and 480 (cm^2 sr MeV/amu)$^{-1}$]. Thus, the observations show no strong preference for large events.

The *ISEE 3* and *Helios* instruments are not equally sensitive to ^{3}He-rich events. The geometry factor of the *Helios* instruments is a factor of 1.7 larger but its energy threshold is much higher than that on *ISEE 3*. For comparison, if we assume a differential energy spectrum of the form E^{-3}, the 1.35–1.65 MeV/amu interval on *ISEE 3* should yield 4.5 times as many particles as the 5–8 MeV amu^{-1} interval on *Helios*. Most of the 66 events in the Kahler et al. list. would still be observable with a factor of 4.5 reduction in sensitivity. If the particle intensities vary with distance from the Sun, R, at least as fast as R^{-2}, then, when *Helios* is inside ~0.47 AU, it would be more sensitive to ^{3}He-rich events than *ISEE 3*.

4. COMPARISON OF THE MULTISPACECRAFT EVENTS

Examples of the events that are seen on more than one spacecraft are shown in Figures 2–4. Each figure contains a map of the ecliptic plane showing the locations of the observing spacecraft and the kilometric radio trajectory of the type

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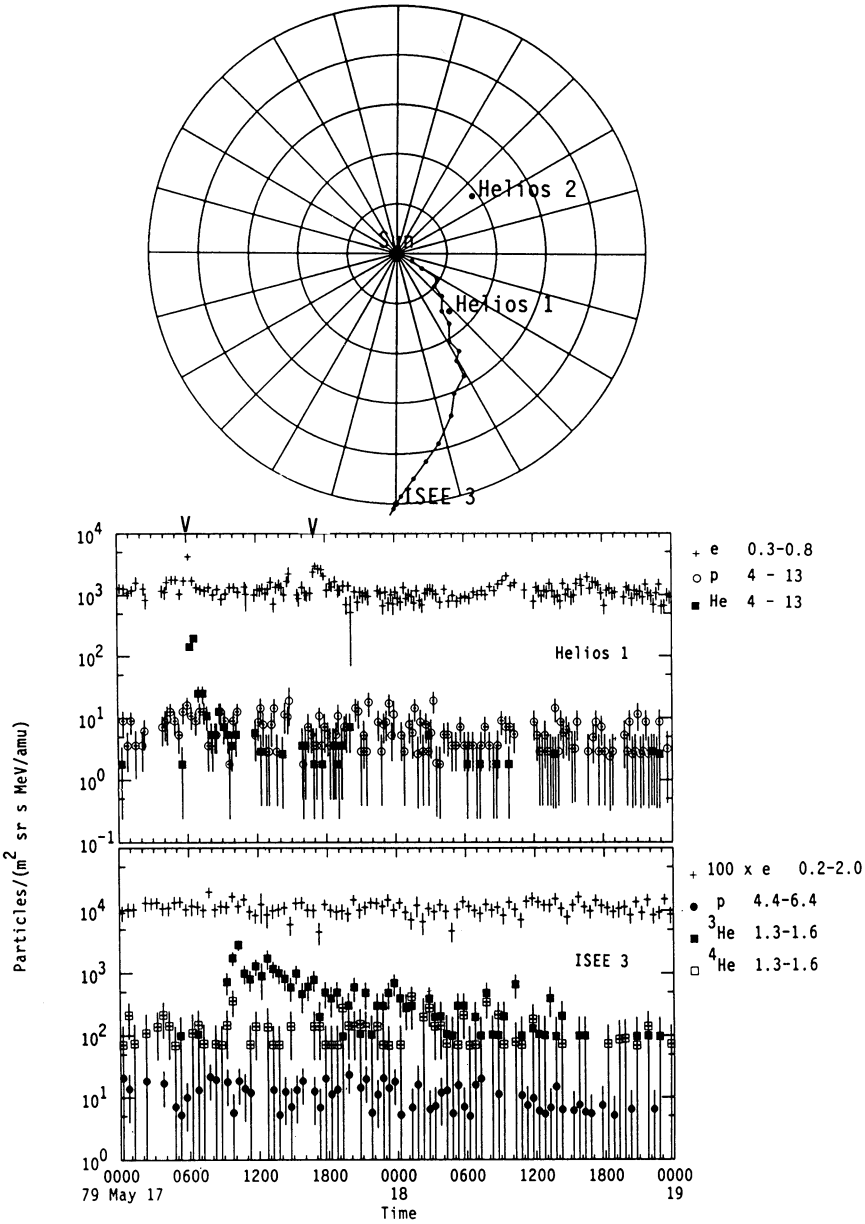

FIG. 2.—The upper panel shows the locations of the spacecraft in the ecliptic plane and the trajectory of the type III radio burst for the 1979 May 17 event. Time histories of electrons, protons and He at the indicated energy in MeV, or in MeV per amu for He, are shown for *Helios 1* in the next panel. The lowest panel shows the time histories of electrons, protons, ^{3}He and ^{4}He at the indicated energies in MeV or MeV per amu observed on *ISEE 3*. Arrows above the uppermost time history mark the onsets of the events listed in Table 1. In the event beginning near 0600, the intensity of ^{3}He is a factor of 10 larger than that of either ^{4}He or protons at both spacecraft.

III burst from the dominant flare of interest. *Helios* time profiles are shown for 0.2–0.8 MeV electrons and for 4–13 MeV amu^{-1} protons and He. ^{3}He/^{4}He ratios for *Helios* are presented separately in Table 1 below. For *ISEE 3* we show time profiles of electrons and protons at energies similar to those for *Helios*, however, we show separate profiles for ^{3}He and ^{4}He at 1.3–1.6 MeV amu^{-1}. The lowest energy He isotopes provide the best information on the course of the event because of improved statistics. As a consequence, however, the He profiles on *ISEE 3* will suffer an additional delay of at least 2 hr, solely because of the velocity dispersion.

Figure 2 shows the 1979 May 17 event seen by *Helios* 1 and *ISEE 3*. This event was discussed originally by Reames, von Rosenvinge, & Lin (1985) and has become the classic extreme example of a ^{3}He-rich event. Electrons and ^{3}He are the only two species that are observed to increase in the event. Not only is the ^{3}He/^{4}He ratio observed to be large on both spacecraft (see Table 1), but also the ^{3}He/proton ratio is seen to be greater than 10 at above 4 MeV amu^{-1} on *Helios 1* and it is also greater than 10 above 1 MeV amu^{-1} as seen by *ISEE 3* (1 MeV protons are not shown in the figure). Notice that the radio trajectory of the IP magnetic field line appears to thread both spacecraft. Mason et al. (1989) fitted the time profiles for the 1979 May 17 event on both spacecraft using solutions to the Boltzmann equation for transport that includes both scattering and adiabatic focusing. Finally, there is evidence of a second

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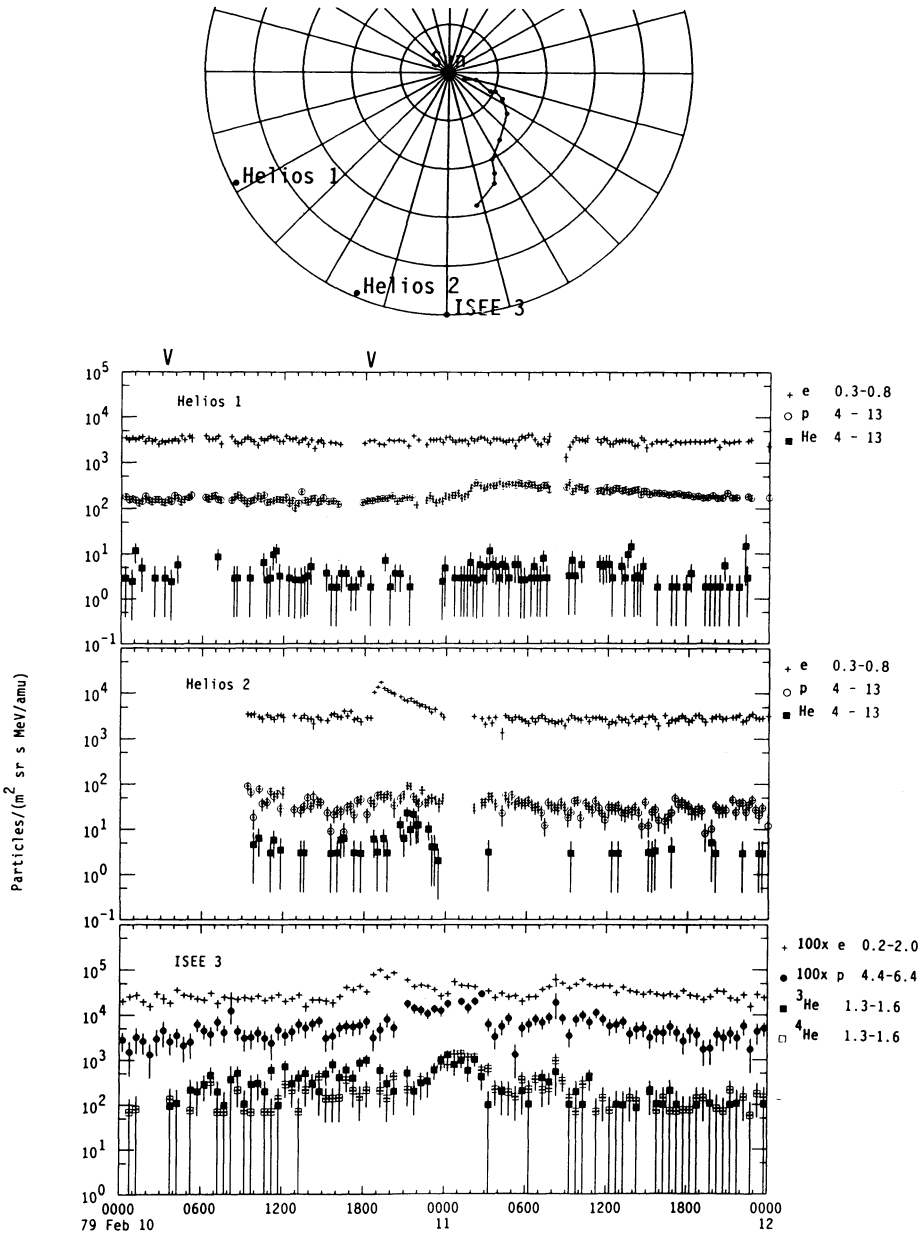

FIG. 3.—Spacecraft locations, radio trajectory, and particle intensities (as described in Fig. 2) for the 1979 February 10 event period (see text)

TABLE 1

^{3}He/^{4}He RATIOS

Radio Onset	*ISEE 3* (1.3–1.6 MeV amu^{-1})	*ISEE 3* (3.0–4.0 MeV amu^{-1})	*Helios 1* (5–8 MeV amu^{-1})[a]	*Helios 2* (5–8 MeV amu^{-1})[a]
1979 Feb 10 0310[b]	2.34 ± 0.36	2.1 ± 0.5	...	$0.3^{+0.4}_{-0.2}$
1979 Feb 10 1820	0.83 ± 0.12	0.85 ± 0.18	...	$0.5^{+0.4}_{-0.2}$
1979 May 17 0550	$8.4^{+\infty}_{-1.7}$	$17.^{+\infty}_{-10}$	$13.5^{+42.}_{-7.2}$	...
1979 May 17 1700	2.1 ± 0.4	1.5 ± 1.2	$1.0^{+4.8}_{-0.8}$	...
1979 Dec 18 1900[b]	2.2 ± 0.8	1.1 ± 1.6	0.025 ± 0.025	<0.09
1979 Dec 21 0730	0.91 ± 0.33	0.16 ± 0.17	...	$0.05^{+0.04}_{-0.03}$
1981 Jun 17 0930	0.31 ± 0.09	0.59 ± 0.21	$0.28^{+0.1}_{-0.02}$	...

[a] Ratio derived from the intervals 5.0–8.4 MeV amu^{-1} for ^{3}He, 4.5–8.0 MeV amu^{-1} for ^{4}He.
[b] Multiple flares may contribute.

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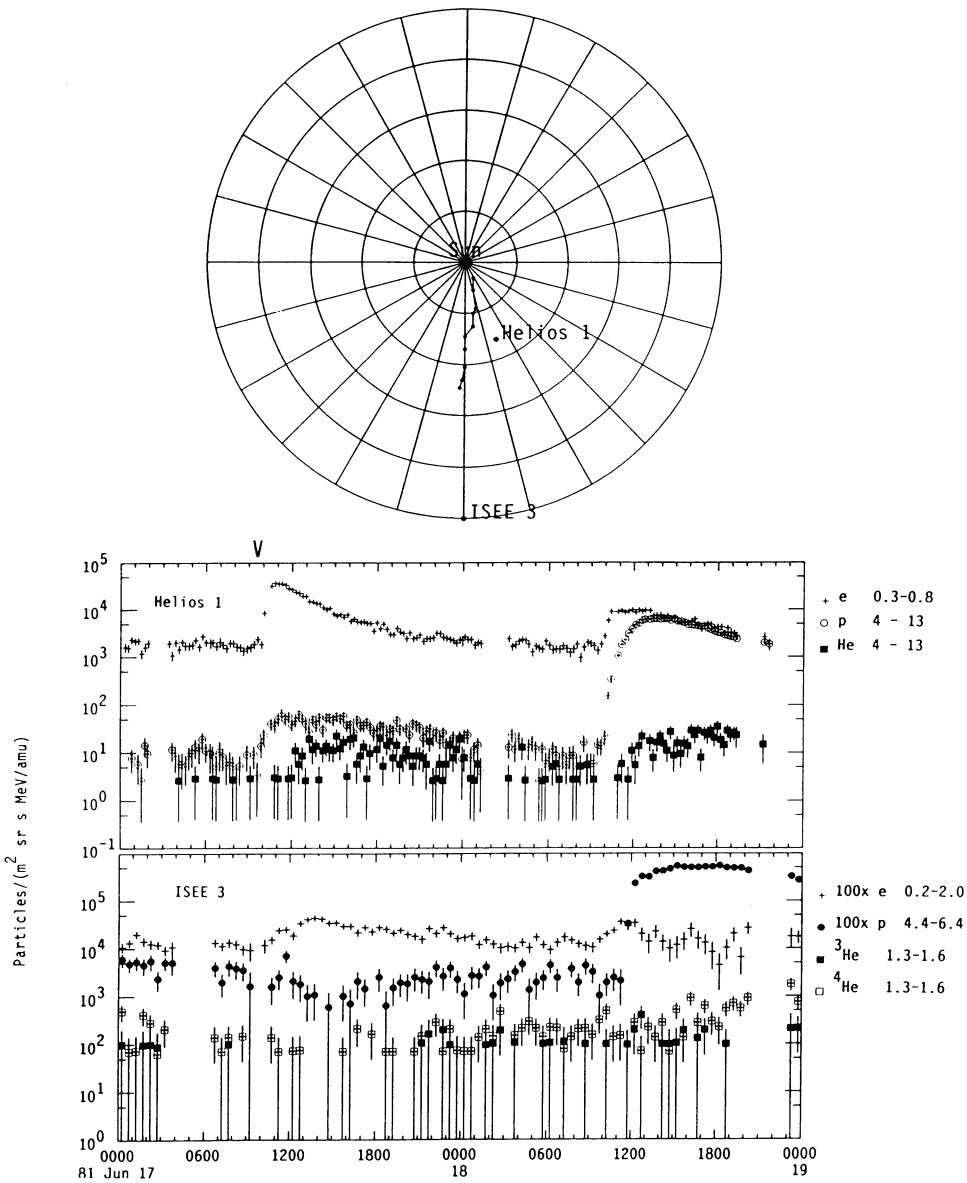

FIG. 4.—Spacecraft locations, radio trajectory, and particle intensities (as described in Figure 2) for the 1981 June 17 event period. Note the contrast in the *p/e* and *p*/He ratios between the ^{3}He-rich event on June 17 and the large proton event on June 18, especially as observed by *Helios 1*.

event beginning with a small electron increase at ~1700 at *Helios* that may contribute to the reduced ^{3}He/^{4}He ratio seen later on *ISEE 3*.

Figure 3 shows an event on 1979 February 10 that may possibly be seen by all three spacecraft. Unfortunately, it is not possible to track the radio emission beyond ~0.5 AU, however, comparison of the electron profiles indicates that *Helios* 2 is best connected to the flare. The He increase from the event begins about 2000 on *Helios 2* and around 2300 on *ISEE 3*. A weak increase in protons and He early on February 11 at *Helios 1* may result from the event, however, pulse-height data are not sufficient to measure the ^{3}He/^{4}He ratio on this spacecraft. If the identification is correct, then this is the widest angular separation over which a ^{3}He-rich event is observed. However, the ^{3}He and ^{4}He profiles on *ISEE 3* show evidence of multiple ^{3}He-rich events on February 10 after 0300. In the presence of multiple events, it is even more difficult to be certain of the association of the weak event at *Helios 1*.

As a final example, Figure 4 shows the 1981 June 17 period. A strong electron increase and an event with a high He/proton ratio are seen on *Helios 1*. A very weak ^{3}He-rich event is seen on *ISEE 3* after a long delay of nearly 9 hr, although an electron increase is seen promptly. The radio trajectory indicates that the field line has been distorted into a nearly radial configuration in the inner heliosphere. Subsequently, on June 18, a large shock-associated (metric type II radio emission) event injects a huge number of protons into space with little or no increase in He at either spacecraft. The contrast between the two events at *Helios 1*, in terms of the electron-proton and He/proton ratios, is striking.

A comparison of the ^{3}He/^{4}He ratios observed in the individual events that can be distinguished is shown in Table 1. Onset

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times in the table are the earliest onsets of the kilometric type III bursts associated with the events (some of the events have multiple bursts). The events on 1979 May 17 clearly show that the same isotopic abundances can be observed, even on widely separated (0.6 AU) spacecraft. This is consistent with the findings of Hempe et al. (1979). The events in 1979 December in Table 1 show different ^{3}He/^{4}He ratios on different spacecraft. It is not possible to determine whether these differences represent true longitude variations within an event or if the spacecraft are sampling particles from different events that have been incorrectly associated.

5. CONCLUSIONS

We have compared *ISEE 3* and *Helios* observations of solar ^{3}He-rich events over nearly all of the time span where such comparisons are possible, greatly extending the comparison time coverage from that of the *Helios 1–Helios 2* study of Hempe et al. (1979). The 1978–1982 study period includes the time of solar maximum so that many impulsive flares leading to ^{3}He-rich particle populations occur. It is likely that over 200 individual flares contribute to the particles in the 66 time periods that we study. Despite these favorable circumstances, relatively few confirmed simultaneous observations of events are found.

Generally, we are unable to observe events when a spacecraft lies at a longitude more than 20° away from that of the field line from the flare. In many cases we cannot observe events even when separated by less than 20° in longitude. Unfortunately, it is not possible to deduce a quantitative full-width at half-maximum for the longitude distribution because of the differences in energy thresholds of the instruments and the meager statistics. However, the observations are not really inconsistent with the 5°–10° width suggested (Reames & Stone 1986) by observations of the time required for passage of a multievent active region.

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