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ENERGY SPECTRA OF IONS FROM IMPULSIVE SOLAR FLARES

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ABSTRACT

We report on a study of the energy spectra of ions from impulsive solar flares in the 0.1–100 MeV region obtained from the combined observations of three experiments on the *ISEE 3* and *IMP 8* spacecraft. Most of the events studied are dominated by He and these He spectra show a persistent steepening or break above ~10 MeV resulting in an increase in the power-law spectral indices from ~2 to ~3.5 or more. Spectra of H, ^{3}He, ^{3}He, O and Fe have spectral indices that are consistent with a value of ~3.5 above ~2 MeV amu^{-1}. One event, dominated by protons, shows a clear maximum in the spectrum near 1 MeV. If the roll-over in the spectrum below 1 MeV is interpreted as a consequence of matter traversal in the solar atmosphere, then the source of the acceleration would lie only ~800 km above the photosphere, well below the corona. Alternative interpretations are that trapping in the acceleration region directly causes a peak in the resulting ion spectrum or that low-energy particles encounter significant additional scattering during transport from the flare. In two of the events, the normal velocity dispersion in the arrival of the ions is modulated by the passage of spatial structures in the interplanetary plasma. One of these events was previously interpreted as a "channel" of continuous particle emission from the Sun; we find no evidence for this interpretation.

Subject headings: Sun: flares — Sun: particle emission — Sun: X-rays, gamma rays

1. INTRODUCTION

In the last few years, it has become clear that particle acceleration in impulsive solar flares differs significantly from that seen in the large gradual events that produce intense interplanetary proton events (see Reames 1990 and references therein). Electron-, ^{3}He-, and Fe-rich particle abundances accompany type III radio bursts and impulsive bursts of both hard and soft X-rays that define impulsive solar events. Highly ionized (+20) Fe ions suggest that the material is heated to $\sim 2 \times 10^7$ K prior to, or during, the acceleration (Luhn et al. 1987). In contrast, ions observed in large proton events usually show abundances and charge-state temperatures typical of the ambient material in the corona or solar wind that might be expected from acceleration by a shock wave well away from the flare-heated region.

Energy spectra of electrons also distinguish impulsive and gradual flares (Evenson et al. 1985). The former show complex spectra that harden above a few MeV, while the latter are easily fitted by shock acceleration models. Recently, Lin (1990) has found low-energy turnovers in the spectra of impulsive-flare electrons. He relates these turnovers to the amount of material traversed by the electrons after they leave the acceleration site deep in the corona.

Energy spectra of ions have been studied less completely than those of electrons. Möbius et al. (1982) studied ion spectra in the 0.5–5 MeV amu^{-1} region in ^{3}He-rich events which were found to be consistent with a model that involves stochastic acceleration by Alfvén waves. In these early studies, however, time intervals of several days were summed to obtain spectra. In several cases, it is clear that multiple flares contributed to these spectra, with different species and energy regions dominated by different flare events. More recently, Mason et al. (1989) reported spectra of several ion species in one ^{3}He-rich event. Also, Van Hollebeke, McDonald, & Meyer (1990) measured spectra in two large impulsive gamma-ray events. However, second-phase acceleration may have contributed to the particles seen in these events. Otherwise, ion spectra in impulsive flare events have not been examined over a broad energy range for evidence of low-energy turnovers or spectral changes that could provide additional information on the nature and location of the acceleration source.

Recent studies of the abundances of accelerated ions deduced from a gamma-ray line flare (Murphy et al. 1991) show that the particles accelerated inside flare loops have the same abundance enhancements as those in impulsive-flare associated particles that we observe at 1 AU. The population of ions that produce the gamma rays clearly do not have the high proton excesses that appear to arise from shock acceleration in the gradual events. The energy spectra used in modeling the gamma-ray line production may also be compared with those seen in space. However, the ion spectra presently used in acceleration studies (see Forman, Ramaty, & Zweibel 1986) and those used to model gamma-ray production come entirely from observations (McGuire & von Rosenvinge 1984) in large gradual events.

In order to extend the observations of ion spectra in impulsive flares to the greatest degree possible with current instruments, we combine the resources of three experiments on the *IMP 8* and *ISEE 3* spacecraft.

2. OBSERVATIONS

During the study period from 1978 August through 1982 August, the *ISEE 3* spacecraft was in orbit about the L1 libration point, 240 Earth radii Sunward of the Earth, while *IMP 8*

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was in a geocentric orbit with a radius of ~40 Earth radii. The *ISEE 3* DFH experiment (Balogh et al. 1978) measures low-energy ions in 8 logarithmically spaced channels from 35 to 1600 keV. Individual ion species are not resolved by this instrument. The *ISEE 3* TYH experiment (von Rosenvinge et al. 1978) resolves elements and isotopes of He above 1.1 MeV amu^{-1}. In terms of total kinetic energy, protons are measured above 1.1 MeV and ^{4}He above 4.4 MeV. Typical resolution of this instrument for He ions is shown by Reames, von Rosenvinge, & Lin (1985, hereinafter RvL). The Goddard Space Flight Center experiment on the *IMP 8* spacecraft (McGuire, von Rosenvinge, & McDonald 1986) resolves protons and He above 4.2 MeV but records only the energies of ions in the 0.88–4.2 MeV region without resolving them. In general, we express observations in terms of total kinetic energy rather than the more usual energy per nucleon since the former allows a smooth extrapolation from the energy regions where particle species are resolved to regions where they are not. The approximate energy coverage of the instruments for H and He is summarized in Table 1.

Candidate events for the spectral studies were derived from lists of ^{3}He-rich events (Kahler et al. 1985; Reames et al. 1988) and electron events (Reames et al. 1990). All of these lists are derived from observations of the *ISEE 3* TYH experiment. For each event, we examined data from the *ISEE 3* DFH experiment for low-energy ions. Generally we required an event to be observable in at least four energy channels in the *ISEE 3* DFH instrument and to exhibit velocity dispersion consistent with that of an impulsive source at the Sun. Velocity dispersion occurs because particle arrival times vary inversely with particle velocity (see RvL). Finally, we did not consider events with type II or type IV radio emission since we wished to rule out any obvious shock or second-phase acceleration that might contaminate the spectra.

Despite an initial sample of well over 100 events, only seven events had sufficiently complete spectral information for study. Furthermore it was not possible to see the events below ~100 keV because of the presence of local particle sources at lower energies, greater difficulty in resolving multiple sources and, perhaps, a variety of other reasons. The events we do present here are relatively intense and most have well-described radio and X-ray properties (Reames et al. 1988).

The intensities that we use for the spectra are determined at the time-of-maximum (TOM) for each energy interval. Van Hollebeke, McDonald, & Meyer (1990) have pointed out that the spectra determined by integration over impulsive events may provide a better representation of the source spectra than do TOM spectra. This is because TOM spectra represent the source spectra only in diffusion-dominated events with low anisotropy. Impulsive flare particles are highly anisotropic and often scatter free (see Reames & von Rosenvinge 1983; RvL; Reames & Stone 1986; Earl 1987). However, the presence of data gaps and spatial discontinuities at low energies has a greater effect on determination of integrals than on determination of TOM intensities since it is often easy to see the intensity maximum even when another part of the profile is obscured. Following the intensity maximum to lower velocity also provides a smaller time window for inclusion of particles from a different event. Therefore we use TOM spectra as a matter of practical necessity rather than philosophical conviction. At constant scattering mean free path, weak scattering theory will give a fixed time profile for a given product of velocity and time.

Figures 1 and 2 show time histories that compare *ISEE 3* DFH and *IMP 8* data for 1979 December 14 and September 6 events, respectively. Successive energy or species measurements are displaced by a factor of 10 for clarity. The bottom two channels in each figure compare H and He intensities at the same energy; H and He are not resolved in the remaining channels. He is more abundant than H in both events at the energy where the species are resolved. At a given total kinetic energy, ^{4}He has a velocity that is half that of H, so He arrives later than H. This effect can be seen in the bottom two channels in Figures 1 and 2. In Figure 1 the peak intensity of 4.2–6.0 MeV H, near 2000 UT, nearly falls on top of a 4.6–5.4 MeV He point that is still at background level. He reaches a broad maximum near 2400 UT. In Figure 2, the 4.2–6.0 MeV H, in the bottom time profile, peaks near 1500 UT and returns to background levels before the 4.6–5.4 MeV He reaches a maximum. In this figure especially, the unresolved particles at energies of 3.0 MeV and below have time profiles that resemble He rather than H.

The effects of velocity dispersion can also be seen in the low-energy data in the figures despite the contribution of two species. The onset time is well defined for the large event on December 14 in spite of the presence of a smaller event that begins earlier. This onset can be seen to move to later times as we move to lower energy in the *ISEE 3* DFH panel in Figure 1. The intensities fall sharply across the small data gap near 0300 UT on December 15. In fact, the fast onset of the event is not seen below 238 keV because particles would have arrived after this feature. Spatial features and changes in the magnetic field do affect the observability of particles, especially below ~1 MeV. We will consider these spatial effects further in § 2.1.

The event of September 6 in Figure 2 shows a clearly dispersed onset down to ~100 keV. The group of brief ion enhancements below 100 keV near the time of onset, and the isolated low-energy bursts elsewhere in the figure, are "upstream bursts" due to ions from the Earth's bow shock. These ions are observed when *ISEE 3* is intermittently connected to the bow shock by the interplanetary magnetic field.

In some events, we can exploit the velocity dispersion to distinguish ion species directly at low energies. An example is shown in Figure 3. Here the *IMP 8* observations in the low-energy unresolved channels have been grouped with the resolved protons in the upper panel to show that low-energy

TABLE 1

ENERGY COVERAGE OF THE INSTRUMENTS FOR H AND He

Total Kinetic Energy	*ISEE 3* DFH	*ISEE 3* TYH	*IMP 8*
35 keV–1.6 MeV	H + He	...	...
1–4 MeV	...	H only	H + He
>4 MeV	...	H and He resolved	H and He resolved

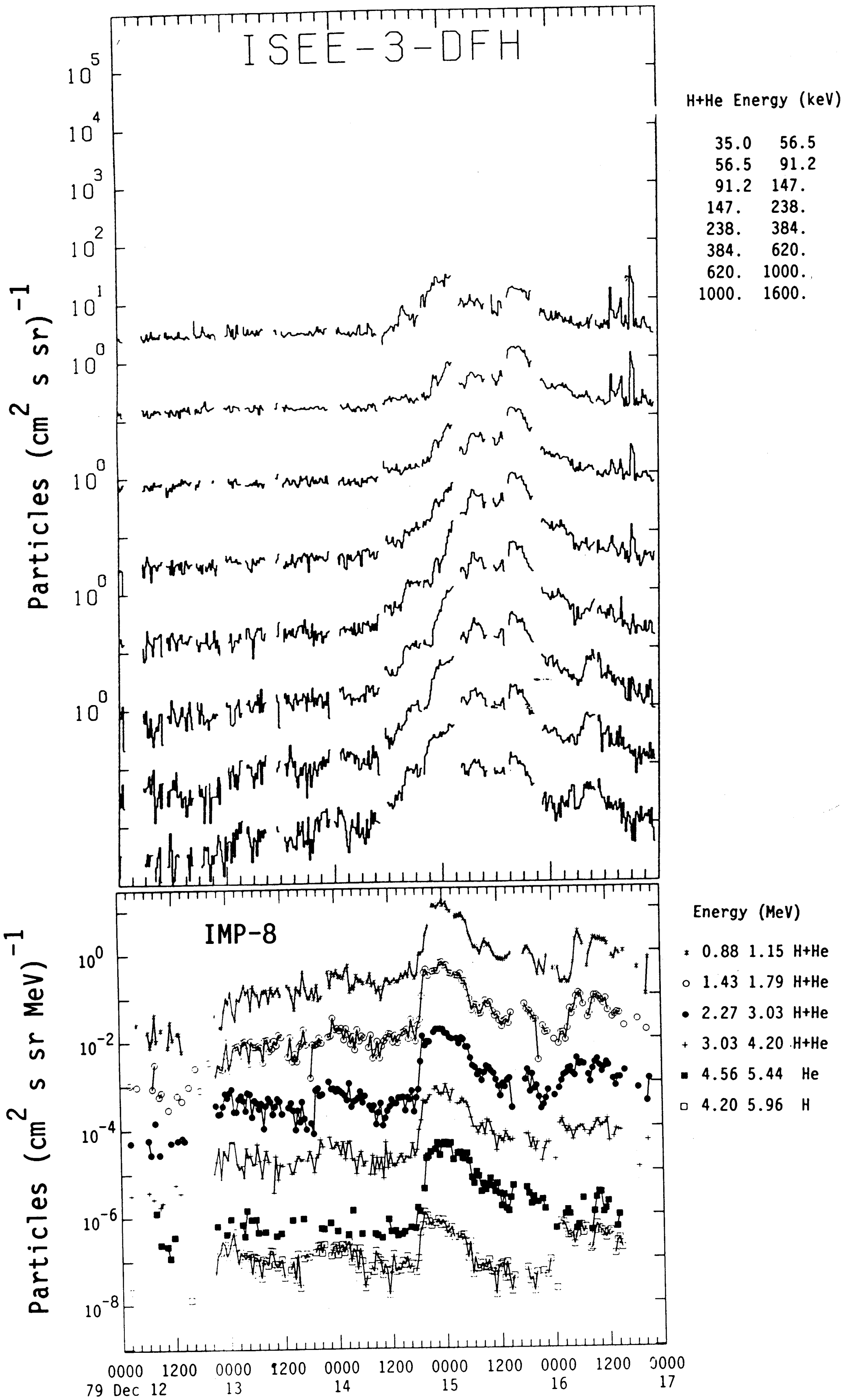

FIG. 1.—Intensities of particles at various total kinetic energies during 1979 December 12–16. Each energy interval or particle species is displaced by a factor of 10 from its immediate neighbor. H and He are only resolved in the bottom 2 channels (at the highest energies). The other channels respond to all ions. The event on December 14 has a rapid onset that occurs later at progressively lower energies. He exceeds H above 4 MeV and the lower energy profiles have the same appearance as the He profile. Intensity profiles such as that at 147–238 keV appear to be truncated during the data gap, probably by passage of a spatial structure in the solar wind plasma (see text).

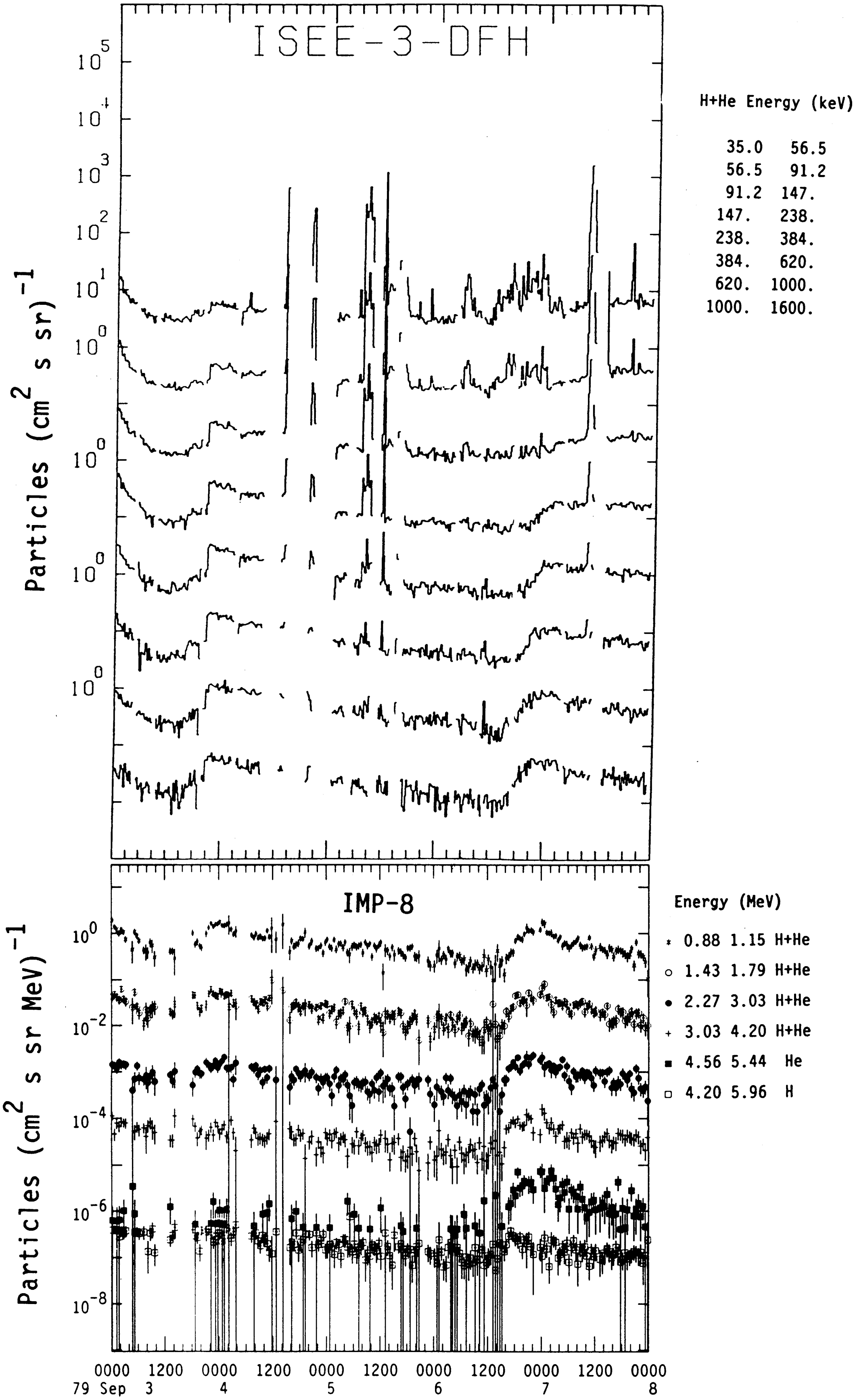

FIG. 2.—Particle intensities for 1979 September 3–7 as described in Fig. 1. The event on September 6 has a smoother profile. The event profiles at lower energy clearly resemble that of He more than that of H. The spikey behavior at the lowest energies is caused by particles from the Earth's bow shock.

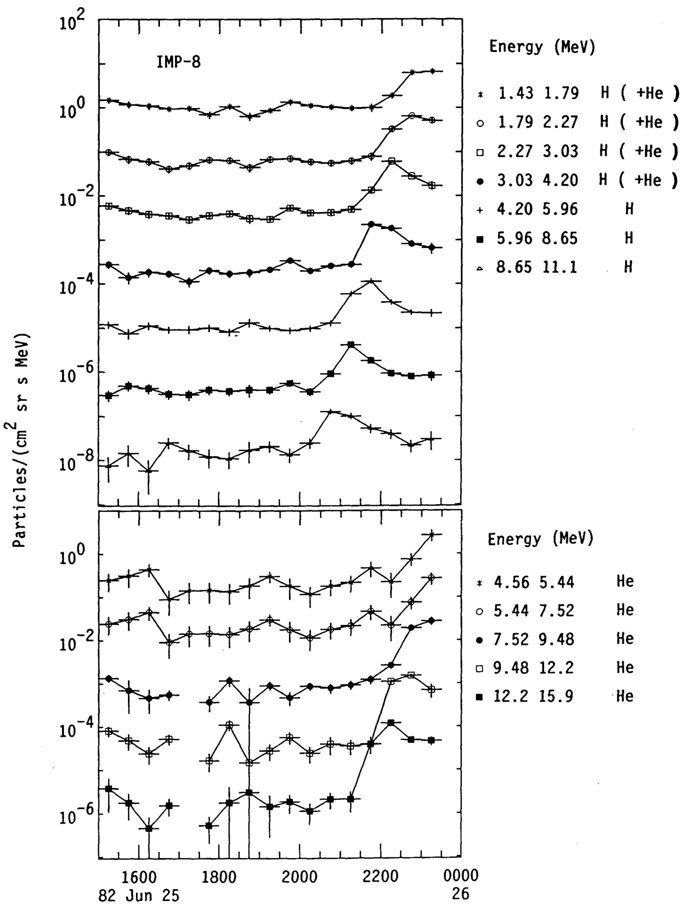

FIG. 3.—Particle intensities on 1982 June 25 clearly show the effect of velocity dispersion in the event. Event profiles in the lowest energy intervals are a continuation of the H (*upper panel*), not the He (*lower panel*), profiles. A long data gap prevents observation at later times.

increases occur at the time when protons are expected. He with energies below 4 MeV would arrive much later as seen by following the progression of the increases in the lower panel. Unfortunately, we are prevented from observing separate peaks for H and He in each single channel at low energies by the presence of a long data gap that begins at the right edge of Figure 3. In events with highly impulsive profiles like this, we can, in principle, combine the ion time-of-flight measurement over the Earth-Sun distance with the energy measurement on the spacecraft to determine the mass of each species observed.

Spectra for the three events discussed above are plotted as a function of total kinetic energy in Figures 4–6. Spectra of the 1979 December 14 and September 6 events are dominated by He in the 4–20 MeV region, and it is very likely that He dominates down to 1 MeV and below. For the 1979 September 6 event, however, the delays in arrival of the particles below ~400 keV suggest that they may be protons rather than He. For the 1982 June 25 event, shown in Figure 6, H and He intensities are comparable above 4 MeV, while the low-energy measurements from *IMP 8* are exclusively protons as we have shown in Figure 3. The apparent depression in the spectrum for this event just above 1 MeV may come from residual effects of data gaps at both spacecraft that have not been fully excluded. All of the He spectra in the figures show evidence of a spectral break above 10 MeV that is especially prominent in

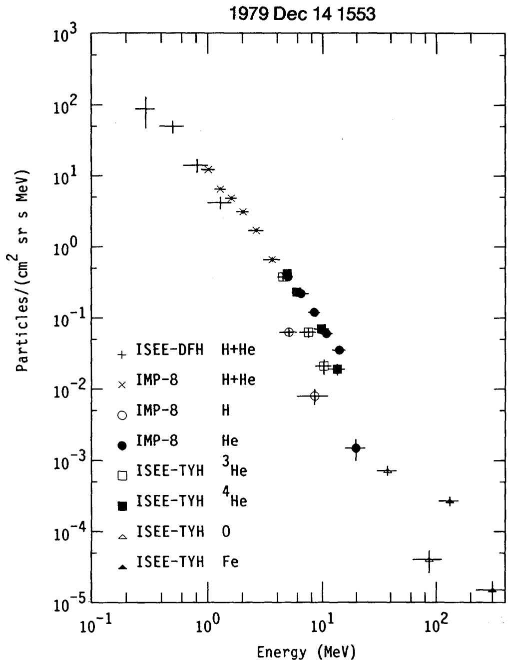

FIG. 4.—Ion energy spectra in the 1979 December 14 event. The He intensity greatly exceeds that of H in the measurements at 4–20 MeV. Above a break in He spectrum at ~10 MeV, heavy ions such as Fe begin to dominate the spectra.

Figure 5. Above the break in the He spectra, heavier ions such as Fe dominate the spectra, as can be seen in Figure 4. We discuss these spectral features further in § 3.

Even though heavy elements such as O and Fe dominate the spectra above ~20 MeV, we are sure that they make little contribution to the spectra in the 100 keV to 1 MeV region where elements are not resolved. At a total kinetic energy of 100 keV, Fe ions have a velocity of only ~600 km s^{-1}. Even at

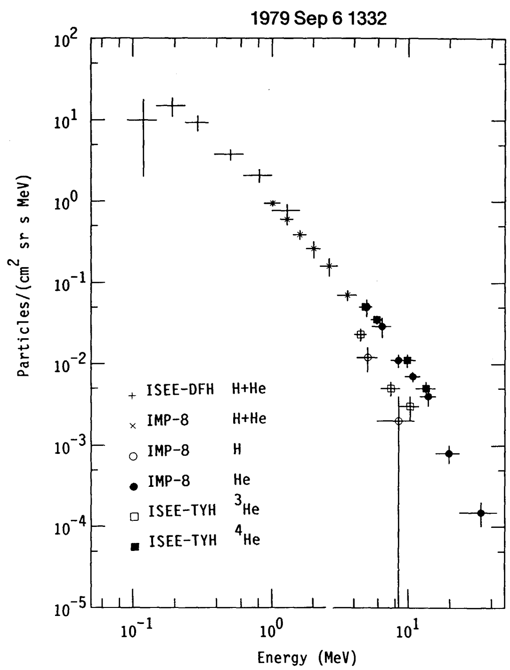

FIG. 5.—Ion energy spectra in the 1979 September 6 event. Note the abrupt steepening in the ^4He spectrum above 10 MeV.

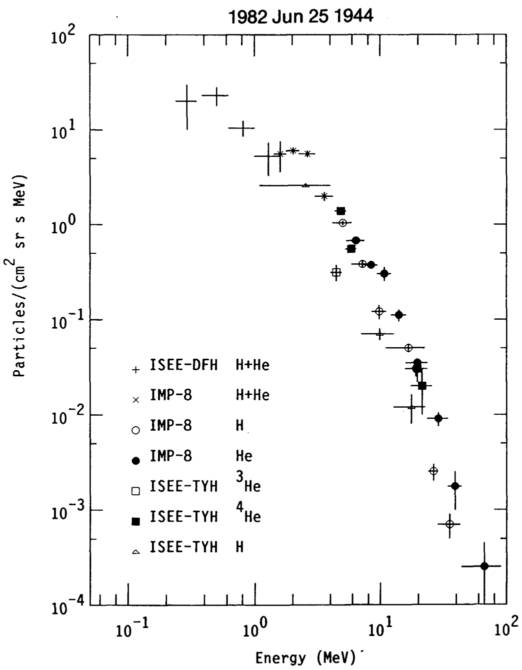

FIG. 6.—Ion energy spectra in the 1982 June 25 event

1 MeV, Fe ions would take a day or more to propagate from the flare to 1 AU and would be easily distinguished from 1 MeV H or He by their late arrival. Using the known velocity dispersion, we have looked for peaks from late arriving heavy ions in the low-energy data but have found none.

In Figure 7 we show spectra from two events in a series of events from a single active region on 1982 August 13 (see Reames & Stone 1986). Both events are dominated by He isotopes in the energy region shown. The spectra of the events are rather different; the earlier event has a power-law behavior over a large interval while the later event has a more rounded spectrum at low energies.

An event of considerable interest is the 1979 May 17 event shown on the left side of Figure 8 since the event appears to consists entirely of ^{3}He. ^{3}He spectra for the event were reported by RvL. The event was also observed on the *Helios 1* spacecraft near 0.3 AU (Mason et al. 1989; Reames, Kallenrode, & Stone 1991). It is found to have ^{3}He/H > 10 as well as ^{3}He/^{4}He > 10 at high energies. Unfortunately, the high pre-existing H background at low energies prevents an unambiguous determination of the low-energy ^{3}He spectrum.

2.1. *Spatial Modulation of the Spectra*

The event of 1979 May 20, also seen in Figure 8, is the classic example of the long-duration "square-wave" intensity profile that Anderson & Dougherty (1986) described as a magnetic channel that "... connects to a region of the solar atmosphere which supplies particles over these long times ...". Particles that populate the channel are associated in some way with a flare at 1107 UT at 65° W longitude on the Sun. Electrons of all energies from 2 to 280 keV arrived from the flare in inverse velocity order while the channel feature was seen primarily in electrons 6 keV and below and in ions below ~1 MeV. Our data show velocity dispersion even in the ion enhancement associated with the channel itself since the onset of the ~200 keV ions occurs after the beginning of the channel.

In Figure 9 we show *IMP 8* particle observations together with the azimuth angle of the magnetic field during the event. From Figure 9, and also from the spectra in Figure 10, it is clear that He dominates H in the MeV ions, as it does in most of the other impulsive flare events that we have discussed above. At 4 MeV, He makes a substantial contribution to the channel region, from 2100 to 0300 UT, partly because it arrives much later than H of the same energy. Just as the low-energy ions begin to arrive, the magnetic field begins an excursion through 120° in azimuth during the 6 hour passage of the

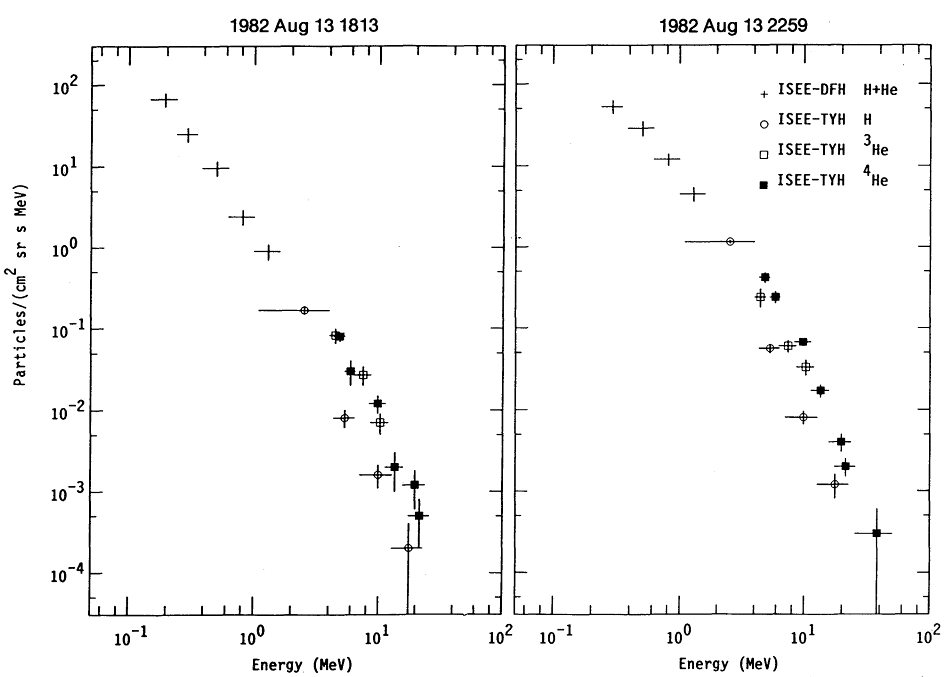

FIG. 7.—Ion energy spectra in the two events of 1982 August 13

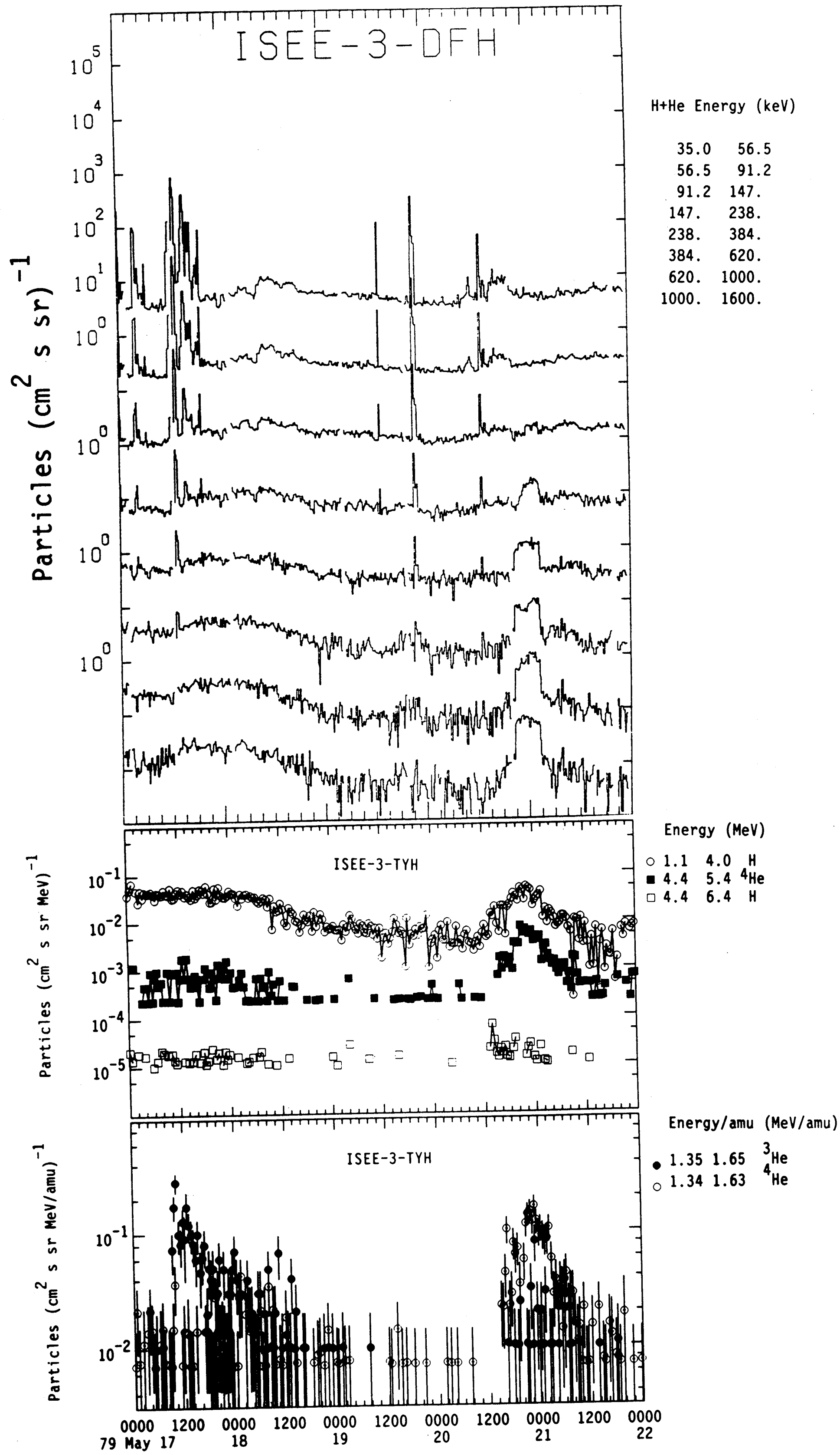

FIG. 8.—Intensity-time profiles for 1979 May 17–21. Successive curves are displaced downward by a factor of 10 in the upper 2 panels. The lower panel shows ^{3}He and ^{4}He intensities at the same energy/nucleon and the same intensity normalization. Only ^{3}He is seen from the event on May 17 while H is obscured by an earlier increase. The event on May 20 was previously identified as a "magnetic channel" event (see text).

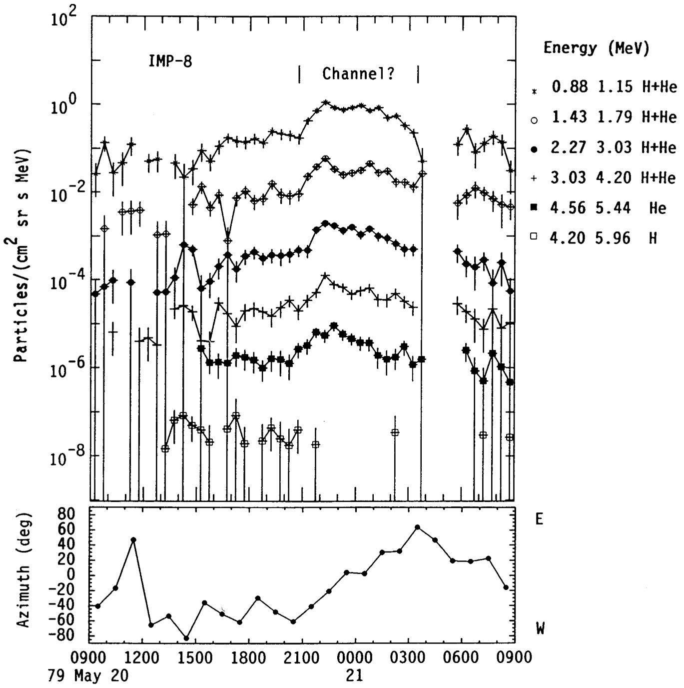

FIG. 9.—Intensity profiles during the 1979 May 20 "channel" event are shown together with the azimuth angle of the magnetic field. The field angle undergoes a large excursion during the channel period. Note that He from the flare dominates H above 4 MeV. As expected, He arrives later than H because of its lower velocity.

channel region. While the topology of the field is uncertain, it is possible that the degree to which the Earth is magnetically connected with the flaring region may change substantially as the field varies. The combination of spatial and temporal variations that we encounter as a function of energy leads to a rather ragged measure of the particle spectra as shown in Figure 10.

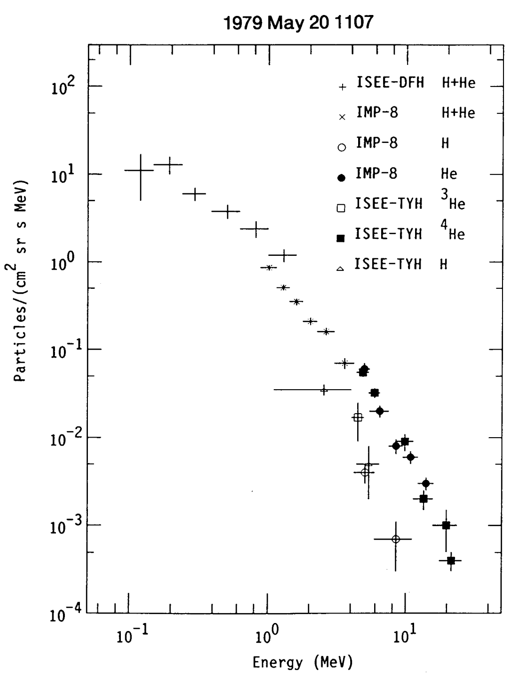

FIG. 10.—Energy spectra of particles from 1979 May 20 event

Based upon these observations, we would describe the May 20 event as a normal impulsive flare event where changes in the magnetic field modify the magnetic connection to the flare prior to and during the arrival of the lowest energy particles. We see no need to invoke extended injection or trapping for this event. Other events studied by Anderson & Dougherty (1986) are too small for us to observe ions above an MeV.

These observations do point out that low-energy ions are susceptible to spatial changes in the magnetic fields. The sharp drop in the intensities at low energies in the 1979 December 14 event shown in Figure 1 is another example of this type of behavior. It is not clear whether there are fundamental differences in the spatial distribution or transport of these particles or if their slow arrival simply increases the probability of changes in the environment before they arrive.

2.2. *Event of 1980 November 17*

One of the most unusual impulsive events that we have observed is shown in Figure 11. The spectra derived from this event are shown in Figure 12. The particles exhibit very clear velocity dispersion in both instruments as shown in Figure 11. We also note that anisotropic field-aligned flow of the particles outward from the Sun along the field lines is also observed, as in all of the other events studied. The event differs from those discussed above in that H is much more abundant than He, and especially, in the distinct roll-over in the proton spectrum below 1 MeV.

We have associated the event with an Hα flare with a 25 minute duration beginning at 1337 UT at 78° W longitude. The flare is preceded by an intense type III metric radio burst at 1333 UT. No type II or type IV bursts are reported that would suggest a presence of an alternative mechanism of acceleration. Thus, we are unable to identify any features of this flare that would distinguish it from the others or explain the unusual behavior of the proton spectrum.

3. SPECTRAL ANALYSIS AND CONCLUSIONS

An examination of the spectral plots for each of the He-dominated events shows evidence of a break in the spectrum near 10 MeV. We summarize the power-law spectral indices for the events at energies above and below 10 MeV in Table 2, and we show fitted spectra for 4 He-dominated events in Figure 13. Typically the spectra break from an index of 2 below 10 MeV to an index of 3.5 or more above. These consistent spectral breaks seems to indicate that the acceleration mechanism becomes less efficient for He particles with energies above ~10 MeV. Notice that the existence of this spectral break does not depend upon our identification of the lowest energy particles as He. In fact, if protons contributed to the low-energy

TABLE 2

POWER-LAW SPECTRAL INDICES IN SELECTED ENERGY INTERVALS

Onset (UT)	Species	Interval (MeV)	Spectral Index	Interval (MeV)	Spectral Index
1979 May 20 1107	He	0.2–10	1.91 ± 0.08	>10	3.75 ± 0.52
Sep 6 1332	He	0.2–10	1.95 ± 0.04	>10	3.47 ± 0.36
Dec 14 1553	He	0.2–10	2.18 ± 0.04	>10	3.74 ± 1.78
1982 Aug 13 1813	He	0.2–10	2.10 ± 0.07	>10	3.74 ± 0.59
Aug 13 2259	He	0.2–10	1.95 ± 0.07	>10	4.26 ± 0.14
1980 Nov 17 1337	H	1–10	2.9 ± 0.6	...	...
1982 Jun 25 1944	H	0.2–10	1.92 ± 0.23	>10	3.91 ± 0.93
	H	0.2–2.0	1.12 ± 0.24	>2	2.90 ± 0.18

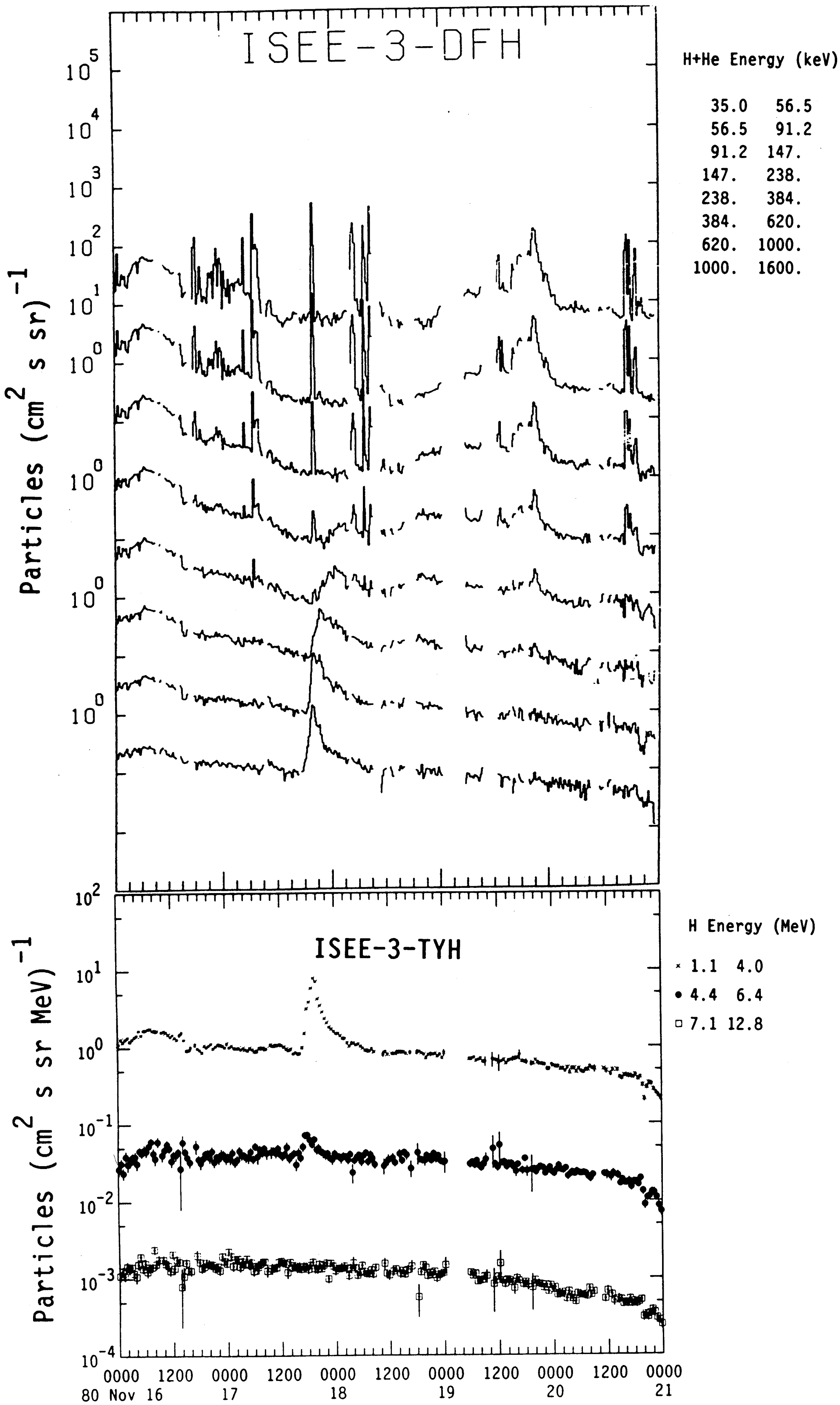

FIG. 11.—Particle intensities in the 1980 November 17 proton event. Successive curves are displaced by factors of 10. Note the rapid decrease in the peak intensity of the channels below 600 keV. Velocity dispersion is clear in the event, and there is no evidence of spatial modulation of the intensities.

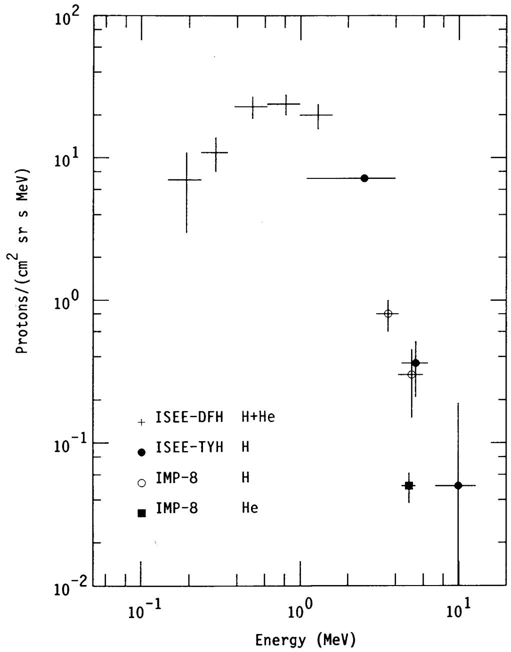

FIG. 12.—Energy spectra in the 1980 November 17 event showing the strong rollover below 1 MeV. The event is dominated by protons.

region, then removing the proton contribution would make the low-energy He spectra even flatter and the break more pronounced.

Proton spectra, such as that shown for the 1982 June 25 event in Figure 6, are rather rounded, so it is difficult to compare them with the He observations to determine whether the spectral break is defined by particle energy or velocity. The dominance of heavier ions at high energies, however, strongly suggests that their spectra are better organized as a function of velocity or MeV per amu. Ions such as O and Fe are observed in most of the events but spectra can be obtained only for the 1979 December 14 event. Ion spectra for this event were shown previously by Mason et al. (1989). The spectral indices for O and Fe, as well as for ^{3}He and ^{4}He, are shown in Table 3 for energies above 2 MeV amu^{-1} (corresponding to 8 MeV total energy for He). The close agreement of the ion spectral indices also suggests that they are organized by MeV per amu or velocity. If a spectral break at $\sim$2 MeV amu^{-1} is truly a characteristic of the impulsive phase, a second phase of acceleration must be required to produce the very energetic ions in the large events observed by Van Hollebeke, McDonald, & Meyer (1990). Spectral breaks are also seen in electron spectra near 100 keV (e.g., Lin 1990), but the relationship between the electrons and the ions is not clear. For constant velocity acceleration, for example, 10 MeV He would correspond to 1.3 keV electrons, where observations in flare events are not available.

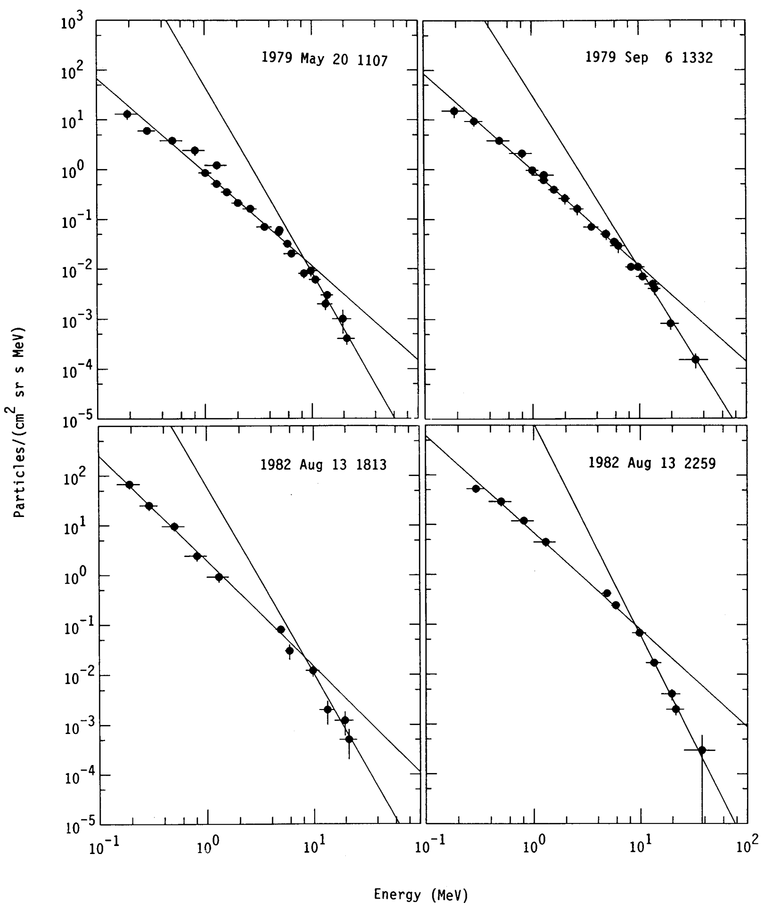

FIG. 13.—Fitted spectra for four events that appear to be dominated by ^{4}He. Separate least-squares fits were made to the ^{4}He intensities above and below 10 MeV.

TABLE 3

SPECTRAL INDICES FOR VARIOUS PARTICLE SPECIES ABOVE 2.0 MeV amu^{-1} IN THE 1979 DECEMBER 14 1533 EVENT

H	4.0 ± 0.6
^{3}He	3.4 ± 0.2
^{4}He	3.3 ± 0.7
O	3.4 ± 0.5
Fe	3.4 ± 0.4

Spectral measurements at low energies can be complicated by the existence of velocity dispersion. Between the times of arrival of the high- and low- energy particles, many things can happen. Data gaps can selectively obscure a particular energy range. The degree of the magnetic field connection to the particle source may also change as spatial structures in the solar wind pass over the spacecraft. It is possible that low-energy particles are more strongly affected by interplanetary field structures than are those at higher energies. However, we believe that any association between the flare particles and magnetic structures is entirely coincidental; only two of our seven events appear to be affected by field structures. If magnetic channels have an independent identity, it is not related to the presence of particles from impulsive flares, and we see no evidence of continuous emission of particles at the Sun as proposed by Anderson & Dougherty (1986). Furthermore, we would expect that the passage of magnetic structures is as likely to diminish particle intensities as it is to enhance them, as is seen in the 1979 December 14 event dicussed above.

The peak in the spectrum of the 1980 November 17 event is not easy to understand. If, following Lin (1990), we interpret the peak in terms of matter traversal by the protons after acceleration, we find that acceleration must have occurred ~ 800 km above the photosphere (in deriving this value we use the calculations by Hua (1986) that were used to model neutron production in flares). While such an altitude is not impossible, it is substantially below the heights of $\sim 10{,}000$ km near the tops of flare loops where acceleration is generally assumed to occur. Unfortunately, we are unable to study proton spectra in the two events observed by Lin because the ion intensities are too low.

We point out that theoretical spectra have been calculated (see Forman, Ramaty, & Zweibel 1986) that show peaked behavior. If particles do not leak out of a region of stochastic acceleration until late in the event, for example, a spectral peak can result. Thus matter traversal is not the only possible explanation of either the proton or electron peaks. None of the events is sufficiently intense to permit a search for fragmentation products of heavier nuclei that could provide conclusive evidence of material traversal. There is, of course, always a chance that the spectral roll-over results from a change in the interplanetary conditions prior to the arrival of the low-energy particles in this event.

Apart from the 1980 November 17 event, however, three of the other six events show some evidence of flattening or turnover in the 100 keV region. A turnover at this energy would suggest that the events come from altitudes above 2000 km, in the lower corona.

Finally, we call attention to the dominance of He over H among the energetic particles in impulsive flares. In most cases, He carries most of the energy that is available in particles above 1 MeV while ions such as Fe frequently carry most of this energy in particles above 100 MeV. This is also true of the energetic particle beams that interact to produce gamma-ray lines inside the flare loops as reported by Murphy et al. (1991). At constant energy per nucleon, H/He ratios in impulsive flares fluctuate above and below the coronal ratio (Reames, Cane, & von Rosenvinge 1990). Transforming to total energy content using typical spectral shapes, however, leads to the domination of He or Fe. The combination of relatively low H/He ratios and steep spectra above 2.5 MeV amu^{-1} rendered these impulsive-flare–associated particles nearly invisible to early observers looking for protons above 10 MeV.

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