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 to 100 MeV region obtained from the combined observations of 3 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 about 10 MeV resulting in an increase in the power-law spectral indices from ~2 to ~3.5 or more. Spectra of H, ^{3}He, ^{4}He, O and Fe have spectral indices that are consistent with a value of ~3.5 above about 2 MeV/amu. 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. An alternative interpretation is that trapping in the acceleration region directly causes a peak in the spectrum.

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 ~2×10^7 K prior to, or during, the acceleration. 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 fit 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 (Möbius *et al.* 1982) in the 0.5 to 5 MeV/amu region in ^{3}He-rich events where they are found to be consistent with a model that involves stochastic acceleration by Alfvén waves. Van Hollebeke *et al.* (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 low-energy turnovers or spectral changes that could provide additional information on the nature and location of the acceleration source.

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 3 experiments on the *IMP 8* and *ISEE 3* spacecraft.

2. OBSERVATIONS. 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. In terms of total kinetic energy, protons are measured above 1.1 MeV and ^{4}He above 4.4 MeV. The Goddard experiment on the *IMP 8* spacecraft (McGuire *et al.* 1986) resolves protons and He above 4.2 MeV but only records the energies of ions in the 0.88 to 4.2 MeV region without resolving them. In general, we express observations in terms of total kinetic energy rather than the more usual energy/nucleon since the former allows a smooth extrapolation from the energy regions where particle species are resolved to regions where they are not.

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) 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 4 energy channels in the *ISEE 3 DFH* instrument and to exhibit velocity dispersion consistent with that of an impulsive source at the sun. 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 7 events had sufficiently complete spectral information for study. The intensities for the spectra were determined at the time-of-maximum (TOM)for each energy interval.

Spectra for the 1979 December 14 event are shown as a function of total kinetic energy in Figure 1. Spectra of this event are dominated by He in the 4-20 MeV region and it is very likely that He dominates down to 1 MeV and below. The ^{4}He spectrum shown exhibits a rather pronounced break above about 10 MeV and heavy ions dominate the spectrum at higher energies. This spectrum is typical of most of the events studied.

One of the most unusual impulsive events that we have observed is shown in Figure 2. The spectra derived from this event are also shown in the figure. The particles exhibit very clear velocity dispersion in both instruments as shown in Figure 2. 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.

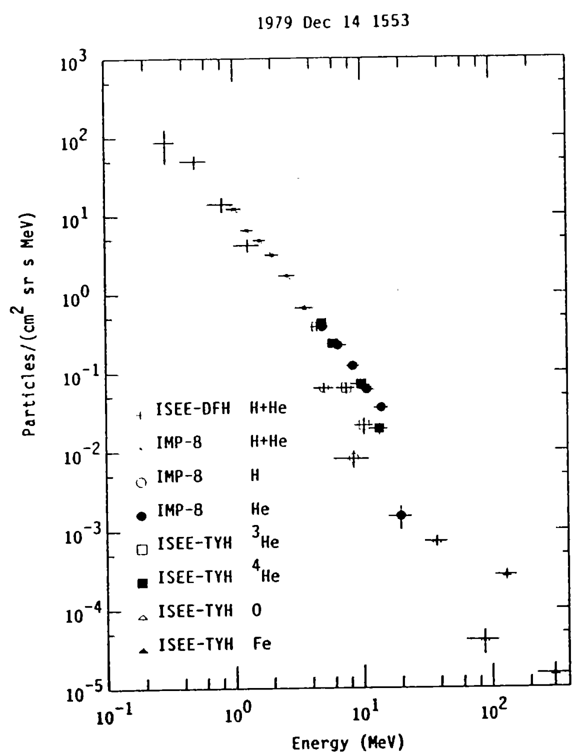

Fig. 1 Typical spectra of ions from an impulsive flare. He exceeds H at 10 MeV.

We have associated the event with an Hα flare with a 25 min duration beginning at 1337 UT on 1980 November 17 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 the 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.

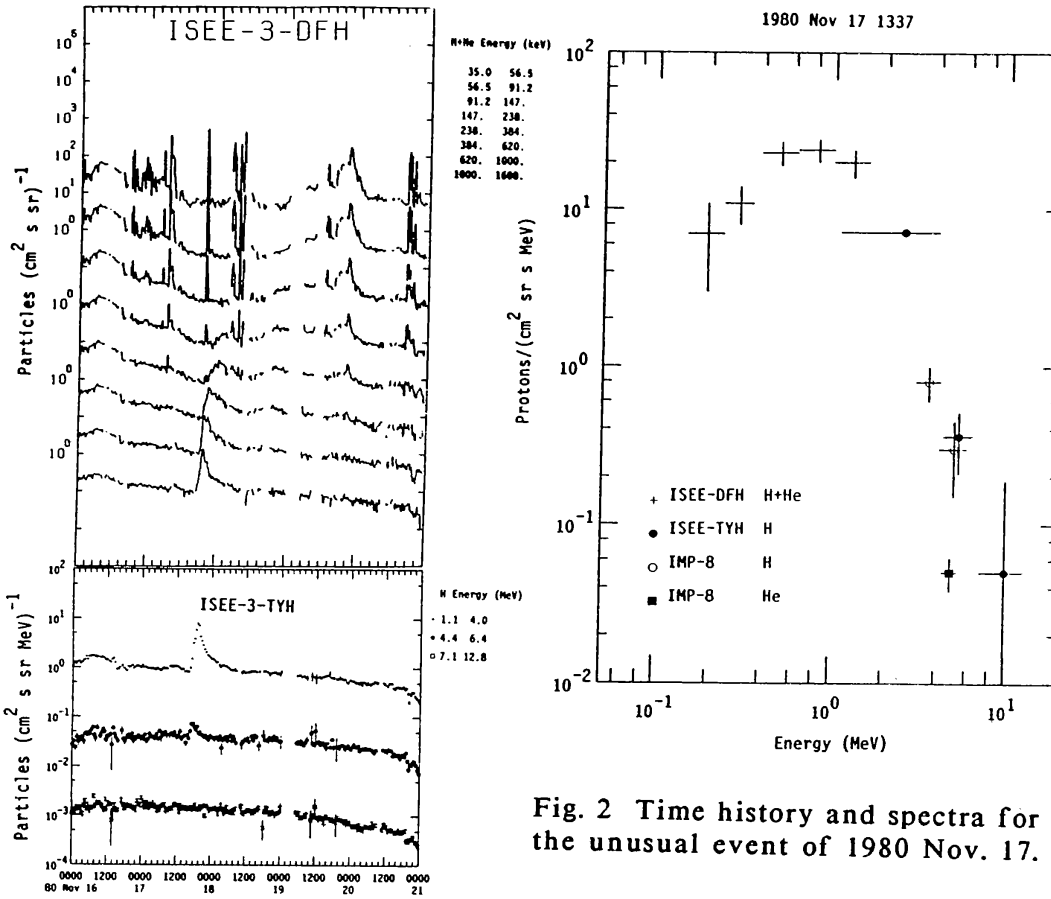

Fig. 2 Time history and spectra for the unusual event of 1980 Nov. 17.

3. SPECTRAL ANALYSIS AND CONCLUSIONS. An examination of the spectral plots for each event (with the exception of the 1980 November 17 event) shows evidence of a break in the spectra near 10 MeV. We show fitted spectra for 4 He-dominated events in Figure 3. 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 seem to indicate that the acceleration mechanism becomes less efficient for He particles with energies above about 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 region, then removing the proton contribution would make the low-energy He spectra even flatter and the break more pronounced.

Unlike He spectra, the proton spectra are rather rounded, so it is difficult to compare them with the He observations. The dominance of heavier ions at high energies, however, strongly suggests that their spectra are better organized as a function of velocity or MeV/amu. The spectral indices for ^{3}He, ^{4}He, O and Fe all agree for energies above 2 MeV/amu. If a spectral break at ~2 MeV/amu 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 *et al.* (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.

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 only about 800 km above the photosphere. As an alternate explanation, we note that theoretical spectra have been calculated (see Forman, Ramaty and Zweibel 1986) that show peaked behavior when the particles do not leak out of a region of stochastic acceleration until late in the event. Apart from the 1980 Nov. 17 event, however, 3 of the other 6 events show some evidence of flattening or turnover in the 100 keV region that would imply an altitude above 2000 km, in the lower corona.

Finally, we call attention to the dominance of He over H among the 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. In terms of MeV/amu, H/He ratios in impulsive flares fluctuate above and below the coronal ratio of 10. The combination of relatively low H/He ratios and steep spectra above 2.5 MeV/amu rendered these impulsive-flare-associated particles nearly invisible to early observers looking for protons above 10 MeV.

The authors thank T. T. von Rosenvinge and R. E. McGuire for their contributions to this work.

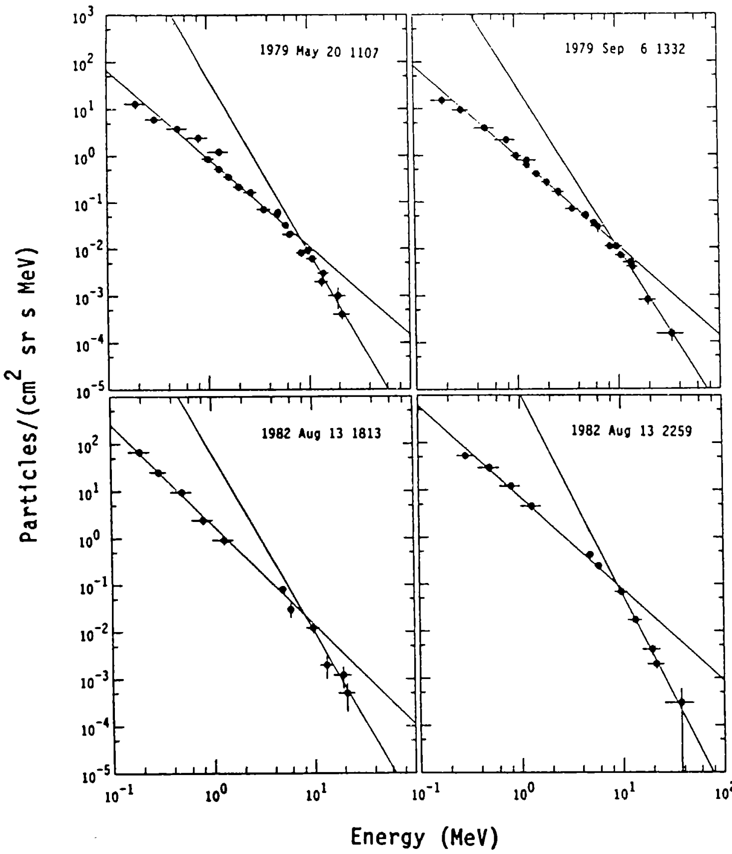

Fig. 3 Fitted ^{4}He spectra in 4 events show a break in spectral slope above 10 MeV.

Balogh,A. *et al.* 1978, *IEEE Trans.* GE-16, 176.

Evenson,P. *et al.* 1985, *19th ICRC.*(La Jolla), 3, 132.

Forman,M.A. *et al.* 1986 in *Physics of the Sun II*, ed. P.A. Sturrock (Dordrecht:Reidel), p 251.

Kahler,S.W. *et al.* 1985, *Ap. J.*, 290, 742.

Lin,R.P. 1990, *21st ICRC.* (Adelaide), 5, 88.

Möbius,E. *et al.* 1982, *Ap. J.* 259, 379.

McGuire,R.E., *et al.* 1986, *Ap. J.*, 301, 938.

Murphy,R.J. *et al.* 1991 *Ap. J.*, 371, 793.

Reames,D.V. 1990, *Ap. J. Suppl.* 73, 235.

Reames,D.V., Cane,H.V., and von Rosenvinge,T.T. 1990, *Ap. J.*, 357, 259.

Reames,D.V., Dennis,B.R., Stone,R.G., and Lin,R.P. 1988, *Ap. J.*, 327, 998.

Van Hollebeke,M.A.I. *et al.* 1990, *Ap. J. Suppl.* 73, 285.

von Rosenvinge,T.T. *et al.* 1978, *IEEE Trans.*, GE-16, 208.