Abstract. Observations of interplanetary relativistic electrons from several solar-flare events monitored through 1964 to mid-1967 are presented. These are the first direct spectral measurements and time histories, made outside the magnetosphere, of solar-flare electrons having relativistic velocities. The 3- to 12-MeV electrons detected have kinetic energies about two orders of magnitude higher than those solar electrons previously studied in space, and measurements of both the time histories and energy spectra for a number of events in the present solar cycle were carried out. These measurements of interplanetary electrons are also directly compared with solar X-ray data and with measurements of related interplanetary solar protons.

The time histories of at least four electron events show fits to the typical diffusion picture. A demonstrated similarity between the electron and the medium-energy proton fits for the event of 7 July, in particular, indicates that at these electron energies, but over several orders of magnitude of rigidity, whatever diffusion does take place is very nearly on a velocity, rather than a rigidity or an energy, basis. Diffusion-fit time histories varied as a function of $T_0$, also indicate that the electrons in certain flare events originate at times near the X-ray and microwave burst, establishing their likely identity as the same electrons which cause the impulsive radiations. Also, the energy spectra and total numbers of the interplanetary electrons, compared with those of the flare-site electrons calculated from X-ray and microwave measurements, indicate that probably a small fraction of flare electrons escape into interplanetary space.

1. Introduction

The existence of many features which frequently accompany large solar flares have demonstrated conclusively that electrons are accelerated by the flare process. These features include energetic X-ray emission as well as the spectral distribution and polarization of types II, III, and IV solar radio bursts. In particular, the impulsive microwave burst and the energetic X-ray emission associated with the explosive phase of the flare, as well as the ensuing type IV radio emission, require electrons to be accelerated to relativistic velocities with the subsequent loss of energy by synchrotron radiation and bremsstrahlung near the flare region (see, e.g., Boischot and Denisse, 1957; Wild, 1962; Takakura, 1967). Type II and type III radio emissions are generally interpreted in terms of lower-energy electrons. There has also been established a very good correlation between type IV solar radio emission and solar cosmic-ray events. However, for many years the study of particle events in interplanetary space had been restricted to the measurements of solar protons and heavier nuclei. It was thus not known whether the absence of interplanetary solar electrons in such events was due to an intrinsic trapping of such particles in the near solar environment or simply to the lack of appropriate instrumentation, until, after one balloon-level observation by Meyer and Vogt (1962), non-relativistic solar electrons were finally found in deep space by van Allen and Krimigis (1965). Their observations and those of Anderson and Lin (1966) showed that intense and prolonged occurrences...
of low-energy electrons (all of which were observed with detector thresholds of around 40 keV) were actually common features of the interplanetary environment, particularly in times of increased solar activity. While the MeV electron results reported here may relate to these low-energy electron measurements, they also represent a natural link to some of the proton data, since the electrons we observed are entirely in the relativistic domain. Further, the interplanetary electrons of energy in the few MeV region must be directly related to those at the sun responsible for the energetic flare X-ray emission and the microwave radio emissions. Hence, detailed correlations between the low- and high-energy electron results, proton and nuclei data, and X-ray observations should provide new information both about the flare process itself and about interplanetary particle propagation.

2. Measurements

Our observations were made with the first three IMP satellites (Explorers 18, 21, and 28) and represent nearly continuous coverage during the 3½ years from November 1963 to May 1967. As shown in Table 1, the first event to definitely contain an intensity of relativistic electrons exceeding our detector threshold occurred on 7 July 1966, although several other solar events were monitored during the preceding several years including the perhaps equally large X-ray and particle event of 24 March 1966. All three satellites had apogees outside the magnetosphere, in particular, the IMP-III apogee was at about 250 000 km, so that long periods of time were spent in interplanetary space, far outside the trapping region in the earth's geomagnetic tail where uninterrupted measurements of solar particles could be made.

The detectors used on all three satellites were identical, the first of which was the one used to detect 3 to 12 MeV interplanetary electrons in solar quiet times (CLINE et al., 1964). It consisted of three scintillators in the familiar energy loss, total energy and guard counter arrangement, providing a geometric factor for stopping particles of about 3 cm² ster. The information telemetered from the experiment consists of two types: (a) detailed pulse-height information on a single stopping particle, and (b) counting rates from individual scintillator arrangements, including the total intensity of stopping particles. The detailed pulse-height data consist of the rate of energy loss and, simultaneously, the residual energy of the first particle (after the commencement of each sampling time) which satisfies the coincidence requirement and does not activate the guard counter. The telemetry rate is fixed such that even in quiet times, pulse-height information can be sampled for only about 1 of every 12 stopping particles. During the peak of the 7 July 1966 event, 1 out of each several thousand stopping particles was identified. The particle selection is however, completely random, so that a valid sample is obtained. The absolute intensity of a particular particle species is thereby measured as a function of time with a statistical accuracy reflecting its proportion in the totality of particles detected. The stopping particles consist of two major groups: 3- to 12-MeV electrons and 16- to 80-MeV protons. The accuracy for observing solar electrons depends on the relative intensity of these two components as well as their absolute flux values. In all cases when we report no electrons were present for