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ENERGETIC PARTICLES FROM IMPULSIVE SOLAR FLARES

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ABSTRACT

Recent observations of the solar energetic particles (SEPs) from impulsive flares are reviewed. In contrast to the particles seen in large proton events, those associated with impulsive flares have an unusual composition that is now understood to be dominated by the effects of wave-particle interactions near the flare site. Impulsive flare events are characterized by high fluxes of electrons that are observed directly and through the type III radio emission that they produce as they propagate outward from the Sun. Ion observations in these events show dramatic enhancements in abundance ratios such as ^{3}He/^{4}He and Fe/O. The heavier ions are observed to be highly ionized by electron collisions in the flare-heated plasma. It is proposed that the observed particles are accelerated stochastically on open field lines near the flare loop by plasma waves generated within the flare loop, and an experimental test of this proposal is suggested. Effects of these low-frequency plasma processes are not observed in the radio, optical, X-ray, or γ-ray emission from the flare but can only be seen in the particle measurements.

Comparison of the SEP abundances with those derived from γ-ray lines, emitted from the ambient flare plasma, can distinguish enhancements caused during acceleration from those that occurred during transport of material up into the corona. Study of the plasma processes that control element abundances at the Sun may have wider application to the understanding of abundances observed in other regions of the Galaxy where direct particle observations are not possible.

Subject headings: gamma-rays: general — Sun: abundances — Sun: flares — Sun: particle emission

I. INTRODUCTION

Dennis *et al.* (1988) have recently completed a list of solar hard X-ray bursts that contains over 8000 events measured during a period of less than 8 years despite a 50% duty cycle for these observations on the *Solar Maximum Mission* (*SMM*). The number of type III radio bursts or Hα flares reported in *Solar Geophysical Data* can also exceed 1000 events per year. Studies of these events suggest that particle acceleration is common in the impulsive phenomena that dominate these observations, yet many observational studies of energetic particles in space have been limited to those rare large events that occur at a rate of a few events per year. Only in the last few years have we begun to distinguish the particles from impulsive flares and from large gradual events and to understand the different physical mechanisms involved in each. It has become clear that the particle characteristics of the numerous impulsive flares differ greatly from those of the large proton events. This paper is a review of this recent work and of our present understanding of the particles from impulsive flares.

Relying mainly on ground-based radio observations, Wild, Smerd, and Weiss (1963) introduced the concept that two distinct mechanisms contribute to particle acceleration in flares. They believed that one mechanism accelerated an impulsive burst of electrons to ~ 100 keV on a time scale as short as a second; these electrons produced a type III radio burst as they moved outward through the corona. A second mechanism occurred in large flares that produced a magnetohydrodynamic shock wave that could accelerate particles to high energies over an extended time. The presence of this second phase was revealed by type II and type IV bursts. This picture was later modified to include acceleration of ions to ~ 100 keV during the first phase (de Jager 1969; Svestka 1976).

Differences between impulsive and gradual acceleration events have now been reported for radio, soft X-ray, hard X-ray, and interplanetary particle observations. Pallavicini, Serio, and Vaiana (1977) observed that soft X-ray events could be divided into two classes: compact events of short duration that occur low in the corona and extended events with long rise and decay times occurring at greater heights. These long-duration soft X-ray events (LDEs) were associated with coronal mass ejections (CMEs) (Sheeley *et al.* 1975; Kahler 1977; Sheeley *et al.* 1983). Impulsive and gradual events have also been distinguished in hard X-ray observations (Ohki *et al.* 1983; Dennis 1985). The latter observations also identify a class of thermal events with no particle acceleration. A precise peak-for-peak temporal association has been made between type III bursts and hard X-ray observations (Raoult *et al.* 1985) in impulsive events. More generally, the presence of type III bursts and hard X-ray emission in a given event presumably requires that electrons can precipitate into the chromosphere and also escape into space on open field lines. Therefore, the probability of seeing both radio and X-ray emission in a given event would be expected to depend upon the altitude of the flare and the geometry of the magnetic field, among other things.

The observation of γ-ray lines from nuclear de-excitation has shown that proton acceleration occurs rapidly during large impulsive flares (Forrest *et al.* 1981; Chupp 1984).

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These findings showed that the impulsive phase of these flares did not accelerate type III–producing electrons alone, although γ-ray lines have been observed in only about 1% of the events with hard X-rays. Thus the nature of the impulsive flare described by Wild, Smerd, and Weiss (1963) required some modification in these large events. Gradual γ-ray events are also observed.

Large proton events dominate the observations of solar energetic particles (for reviews of early observations see Fichtel and McDonald 1967; Ramaty *et al.* 1980). These events are associated with type II and type IV radio emission (Lin 1970; Svestka and Fritzova-Svestkova 1974; Kahler 1982*a*, *b*), and 96% are associated with CMEs (Kahler, Hildner, and Van Hollebeke 1978; Kahler *et al.* 1984). Despite the large type II/IV bursts, these events frequently have no type III bursts. The element abundances in these large proton events reflect the abundances in the ambient solar corona; this has led to the suggestion that acceleration occurs well away from the impulsive flare (Lin 1987). A group of smaller proton events has been associated with disappearing-filament events (Kahler *et al.* 1986; Cane, Kahler, and Sheeley 1986). These events have associated shocks, CMEs, and gradual soft X-ray events but no Hα flares or type III bursts and no visible impulsive phase.

In contrast, nonrelativistic electron events (see reviews by Lin 1974, 1985) are the direct counterpart of the electrons that produce the type III radio bursts in impulsive events, and, as we shall see, it is these electrons that provided the key to identifying the nuclei from impulsive flares. In this paper we do not attempt to examine all of the evidence for two classes of flares except when that evidence helps to define the properties of the particles from impulsive flares. Otherwise we accept the premise that impulsive flares are a well-defined phenomenon based upon evidence that we have discussed briefly above. In studying event classes, it is, of course, the underlying mechanisms rather than the phenomenology that are of paramount interest.

The next three sections of this paper describe the observations of electron events, ^{3}He-rich events, and heavy-nuclei–rich events, respectively. We find that it is possible to combine these observations into a unified description of the particles from impulsive flares. For the numerous small impulsive flares these "uncommon" species *are* the particles from the flare. The small flares provide a unique look at acceleration mechanisms that are obscured in large events by the presence of shocks and CMEs. Section V considers the γ-ray events that provide unique possibilities for comparing particles in the flare with those in space, and, finally, in § VI, an attempt is made to refine the model that describes the acceleration of the particles that are observed.

II. ELECTRON EVENTS

Increases in electrons of 10–100 keV have been observed for many years (Van Allen and Krimigis 1965; Anderson and Lin 1966; Lin and Anderson 1967; Lin 1970) and are the most frequent particle events of solar origin, occurring at a rate of over one event per day or several hundred events per year (see Lin 1974, 1985). The low-energy electrons propagate directly from the solar event along the interplanetary magnetic field lines in a scatter-free mode so that they arrive with a time delay that varies inversely with velocity. Two examples of these solar electron events can be seen in Figure 1, with onsets beginning at 1330 and 2140 UT for the higher energy electrons. These electrons produce type III radio bursts as they propagate outward from the Sun. The observed electrons were believed to be related to the electrons that produce hard X-ray bursts in the solar atmosphere (Lin and Hudson 1976; Lin *et al.* 1981). Only the larger electron events are accompanied by ions; most of the events seemed to be pure electron events, in support of models like that of Wild, Smerd, and Weiss (1963). In their classic paper, Lin and Hudson (1976) examined the energetics of the series of large flares in 1972 August. They found that most of the energy in the flash phase of these events was in the form of 10–100 keV electrons that precipitated into the chromosphere to produce X-rays. Acceleration of energetic protons occurred later, and, unlike the electrons, most of them escaped to the interplanetary medium.

Lin (1974, 1985) presented evidence for a nearly one-for-one association between impulsive flares with type III radio bursts at the Sun and the observation of electrons in space, provided that the flare was magnetically connected to Earth within a cone angle of about 55°. Lin also identified "mixed" events with significant intensities of relativistic electrons. He observed that the high-energy particles arrived after the low-energy ones in these events, contrary to the usual velocity dispersion, and he interpreted this as evidence of second-phase acceleration.

Following the observation of gamma-ray line (GRL) events in impulsive flares (see Chupp 1984), an effort was made to

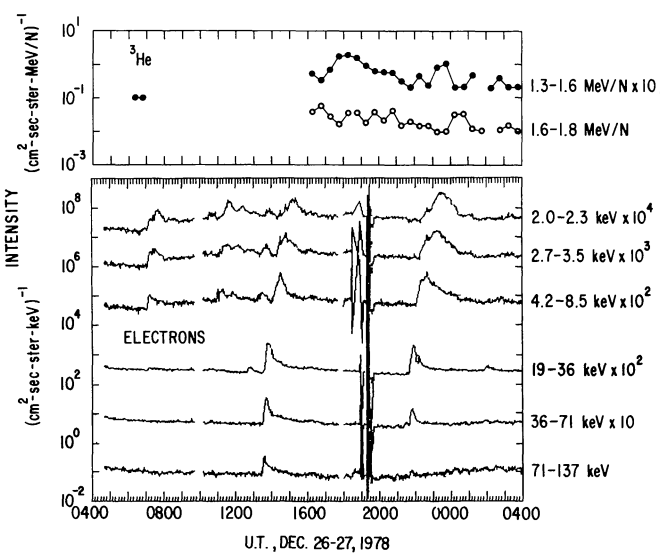

FIG. 1.—Time histories of electrons and ^{3}He of the energies indicated. Velocity dispersion can be seen in the two electron increases that begin at 1330 and at 2140 UT. ^{3}He from the earlier event arrives at about 1600 UT. The ^{3}He traces appear differently because of a lack of continuous background; with the exception of a brief period near 0616 UT, no ^{3}He particles enter the telescope during the first 12 hr of the figure. The electron telescope undergoes a calibration cycle near 1990 UT. (After Reames, von Rosenvinge, and Lin 1985.)

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correlate the number of protons in the event with the number observed in space as discussed in § V. Generally these comparisons are consistent with the idea that many of the protons remain within the flare loops in GRL events (see Ramaty and Murphy 1987). Evenson *et al.* (1984) reported measurements of relativistic electrons in solar events. They identified a class of electron-rich events with high electron/proton ratios (e/p) which they associated with the GRL events. Ironically, these events that are characterized by photons from nuclear reactions induced by protons at the Sun are, like other impulsive events, uniquely proton-poor and electron-rich as observed by the particles in interplanetary space. A model for shock acceleration of the protons in γ-ray events was presented by Bai (1986).

The first systematic study of the properties of particles in space from impulsive and gradual flares at the Sun, was also based upon solar electron events. Cane, McGuire, and von Rosenvinge (1986) determined the flare associations of all events observed in 3 MeV electrons during a period of over 5 years. Events for which soft X-ray measurements were available were divided according to soft X-ray duration in accordance with the classification found by Pallavicini, Serio, and Vaiana (1977). The impulsive events had an average e/p ratio that was more than an order of magnitude larger than that in the gradual events. As shown in Figure 2, events in the two classes had comparable peak fluxes of electrons, but the impulsive events had much lower fluxes of protons than did the gradual events. Cane, McGuire, and von Rosenvinge (1986) also noted that the intensity-time profiles of the impulsive events were much shorter than those of the long-duration events. The use of metric radio data, in conjunction with the X-ray time scales, to distinguish event classes was considered by Cane and Reames (1988). The existence of two classes of event based upon e/p ratios was confirmed by Daibog *et al.* (1987) using different observations.

Concurrently with the work of Cane, McGuire, and von Rosenvinge (1986), Evenson *et al.* (1985) were studying the electron spectra for energetic electron events, and they found that events could be divided into two spectral classes. A comparison of event lists between the two groups revealed that the class of events with power-law spectra in rigidity corresponded in detail to the list of gradual events, while the events with spectra that hardened at higher rigidities corresponded to the impulsive events. Typical electron spectra are shown in Figure 3.

It is important to realize that the discrimination of the particles from impulsive and gradual flares has come from studies of electron (and heavy-ion) events rather than proton events. A search of SEP observations for electron increases yields a high proportion of impulsive events, while a search for proton increases yields very few. A combination of higher proton background and lower proton fluxes from the event, as shown in Figure 2, conspires to reduce drastically the observability of protons from impulsive flares even when they are present.

The comparison of electrons and protons in solar events is complicated by the fact that the two species rarely have similar spectra, and it is not clear what energy, rigidity, or velocity should be used for such a comparison. Fortunately, the difference in the electron and proton characteristics of

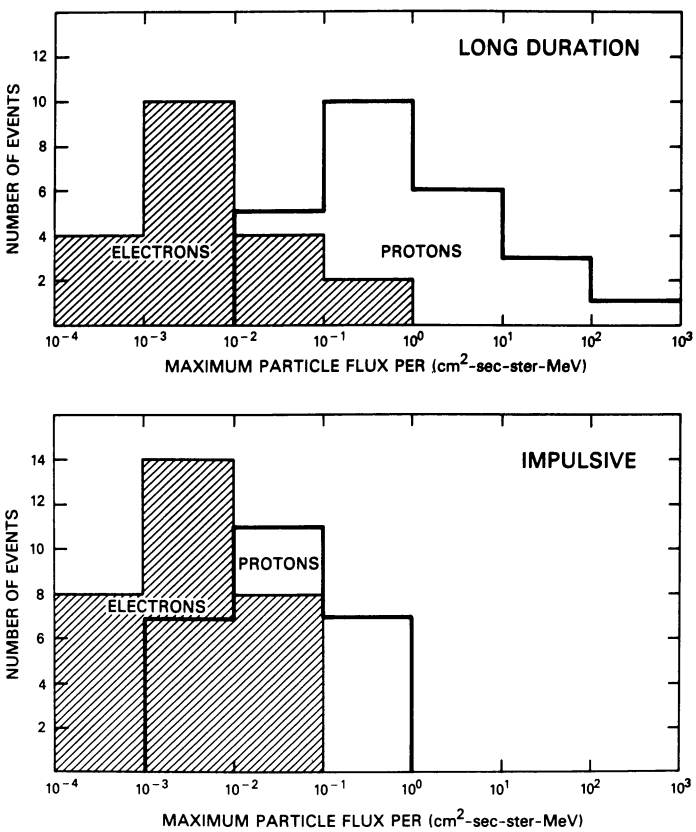

FIG. 2.—Distribution in the fluxes of electrons and protons for events with impulsive and long-duration soft X-ray profiles of the flare. The figure shows the large increase in proton flux associated with long-duration events. From this figure it is clear why the long-duration events are simply called proton events. (After Cane, McGuire, and von Rosenvinge 1986.)

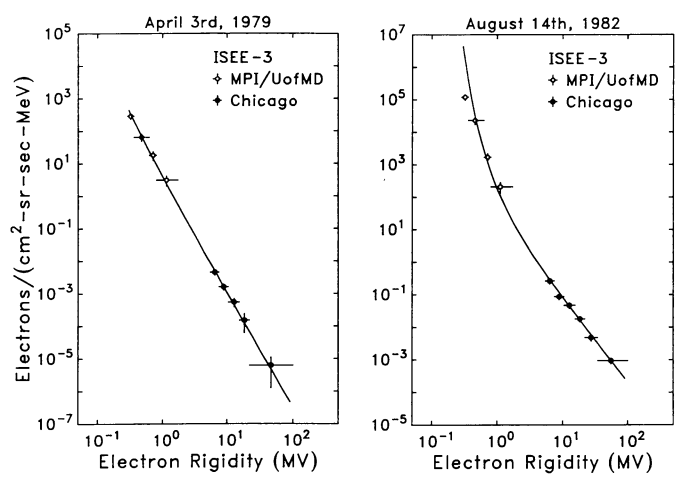

FIG. 3.—Typical electron spectra from solar flares. Electron spectra from impulsive flares, such as that in the right-hand panel, are much harder at high energies than those from gradual events, such as that shown in the left-hand panel. (After Evenson *et al.* 1985. Reprinted with permission.)

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the two classes of events is sufficiently great that it dominates the spectral effects when sufficient numbers of events are examined together. However, spectral variations do tend to blur the distinction between individual impulsive and gradual events so that two distinct peaks in a histogram of e/p ratio, for example, are not observed. It remained for later observations to provide this type of separation of the particles from impulsive and gradual events, as we shall see below.

III. ^{3}He-RICH EVENTS

Solar abundances of He isotopes have been determined by measurements in the solar wind and solar prominences (Coplan *et al.* 1984; Hall 1975) that give $^3\mathrm{He}/^4\mathrm{He} = 5\times10^{-4}$. The observation of $^3\mathrm{He}/^4\mathrm{He} > 1$ in solar energetic particle events (Hsieh and Simpson 1970; Dietrich 1973; Garrard, Stone, and Vogt 1973; Anglin 1975; Serlemitsos and Balasubrahmanyan 1975; Hempe *et al.* 1979; see reviews by Ramaty *et al.* 1980; Kocharov and Kocharov 1984) represents a striking enhancement that is associated with the process of acceleration. In some cases, attempts were made to identify the flares that gave rise to the ^{3}He-rich events, but the identifications were uncertain and the properties of these flares were not distinguished from those of the flares that produced large proton events. In general, the ^{3}He-rich events are small and the frequency of observation of the events has increased with the sensitivity of the observing instruments.

The enhancements of ^{3}He in these events were soon understood to be the result of selective heating by wave-particle interactions in the flare plasma, and several such mechanisms were proposed. Ibragimov and Kocharov (1977) proposed a mechanism based upon interactions with ion-acoustic waves; however, the charge dependence used in this mechanism has been questioned by Weatherall (1984; see also Kocharov and Orishchenko 1985).

Fisk (1978) proposed a mechanism based upon the resonant absorption by ^{3}He of electrostatic ion-cyclotron (EIC) waves that are produced above the ^{4}He gyrofrequency by a high abundance of ^{4}He in the flare plasma. The magnetic gyrofrequency of the ions is $\Omega = qB/\gamma mc$, where q and m are the charge and mass of the ion and B is the magnetic field strength. Thus the gyrofrequency of ^{3}He lies above that of ^{4}He but below that of protons. The condition for resonant absorption of a wave of frequency ω and wavenumber k is

$$\omega = n\Omega + k_{\parallel}v_{\parallel}, \tag{1}$$

where the (signed) integer n is equal to 1 for absorption by ^{3}He in the Fisk (1978) model. The low abundance of ^{3}He allows significant wave absorption and heating without significant wave damping. Heavy ions with a charge/mass ratio of $\frac{1}{3}$ may also interact with the same waves through the second harmonic ($n = 2$) of their gyrofrequency.

The preferential heating causes a relative increase in the ions in the high-energy tail of the thermal distribution for the species that absorb the most energy from the waves. If the particles absorb much energy, however, the last term in equation (1) increases, and the particles no longer resonate with the waves that are produced in a narrow frequency interval. For this reason, the Fisk model, and other resonance models, require that a secondary mechanism accelerate only those particles that have been heated to energies above a specific threshold, thus selecting particles from the region of enhanced abundances.

Varvoglis and Papadopoulos (1983) modified the Fisk mechanism by considering the nonresonant absorption of EIC waves produced by protons. These waves are more likely to be generated than the ^{4}He EIC waves required in the Fisk model. These authors envisioned the heating as a stochastic process involving a nonlinear interaction of the ^{3}He with the waves. The preferential heating comes about because of extreme variations in the threshold for the nonlinear interaction rather than from resonant absorption.

The mechanisms described above were all devised to enhance selectively the high-energy part of the thermal distribution but not to accelerate the particles to MeV energies. Möbius *et al.* (1982) calculated particle spectra based upon further acceleration by the stochastic Fermi mechanism in an environment of Alfvén turbulence (see also Forman, Ramaty, and Zweibel 1986). Möbius *et al.* (1982) were able to explain the observed spectra of He and heavy nuclei with their model (these authors simulate the interaction with a hard-sphere diffusion constant). Alfvén waves interact with particles only when their velocity exceeds the Alfvén velocity. The interaction obeys equation (1) with small values of ω, so that the other two terms dominate the equation, requiring significant threshold particle velocities.

Evidence for the connection between ^{3}He-rich events and impulsive flares was presented by Reames, von Rosenvinge, and Lin (1985; hereinafter RvL), who found a close temporal association between ^{3}He-rich events and nonrelativistic electron events. Figure 1 shows an example of this association. Like the electrons, the ^{3}He from an event arrives with a time delay that varies inversely with its velocity; thus the ^{3}He in the 1.3–1.6 MeV amu^{-1} interval arrives about 2.5 hr after the highest energy electrons. This relationship between the time of onset or of maximum intensity and the particle velocity is shown quantitatively for a different event in Figure 4. The arrival time of a particle is approximately $L/(v\cos\theta)$,

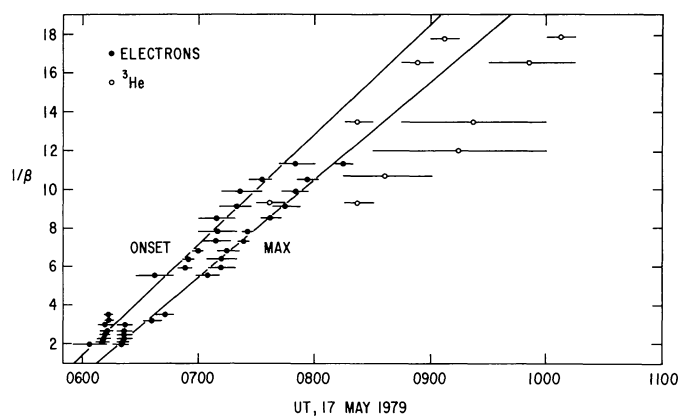

FIG. 4.—Time of onset and of maximum intensity for the particles indicated vs. $1/\beta$, showing the velocity dispersion. The lines are a least-squares fit of the electron data. A linear relationship means that the arrival time is simply distance/velocity. (After Reames, von Rosenvinge, and Lin 1985.)

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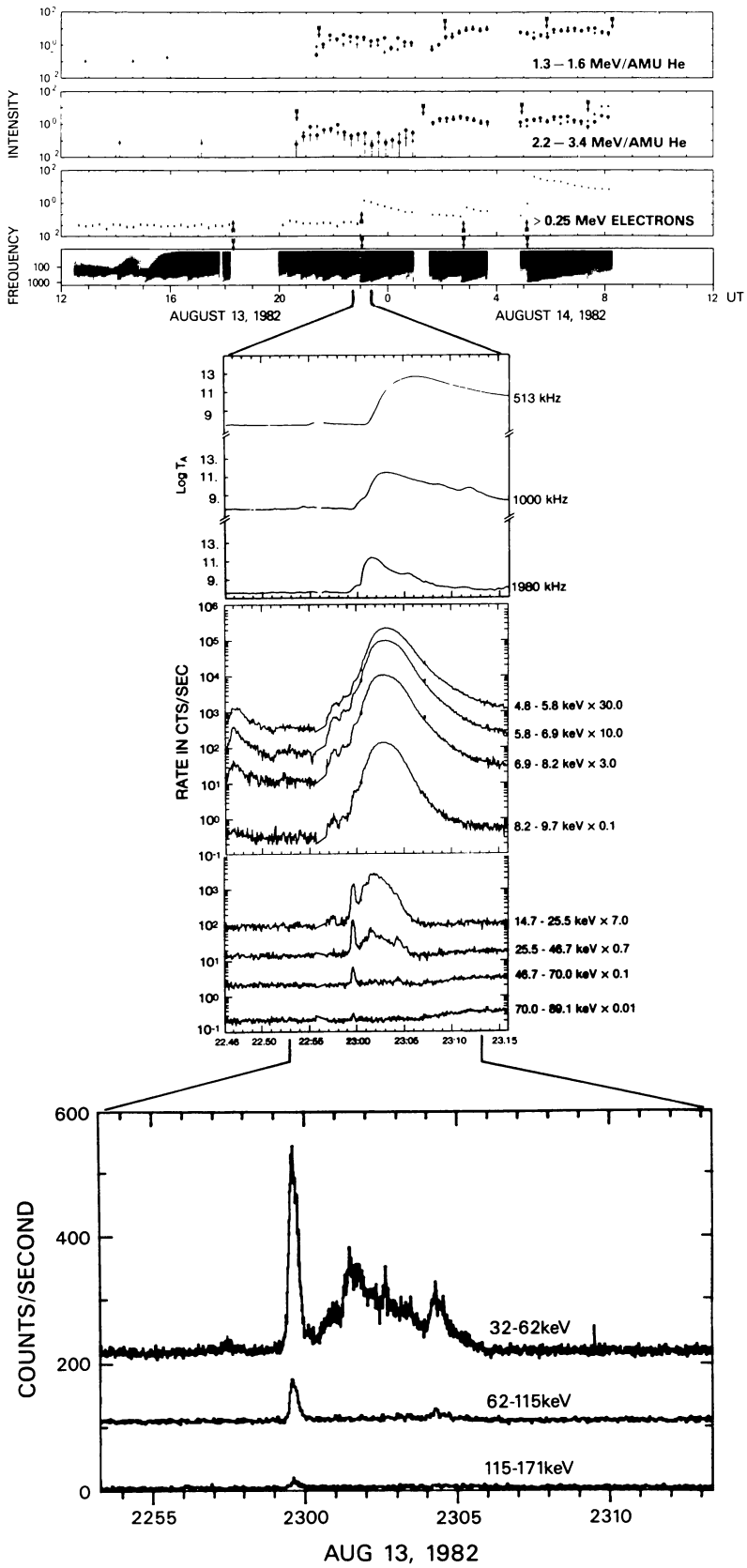

FIG. 5.—Composite figure showing the temporal relationship of particle, radio, and X-ray data for one event in a series of ^{3}He-rich events (see text). (After Reames and Stone 1986; Reames *et al.* 1988.)

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where L is the length of the magnetic field line from the Sun and $v \cos \theta$ gives the component of the particle velocity along the field. ^{3}He is delayed relative to electrons in Figure 4 because it has a broader pitch angle (θ) distribution arising from increased scattering by irregularities in the field. The surprising feature of the RvL work is the small amount of scattering in ^{3}He-rich events relative to the amount that had been deduced in large proton events. The time from the flare onset to maximum intensity of 1–2 MeV particles is typically 2.5 hr in ^{3}He-rich events, compared with over 12 hr for the large proton events. The assumption of long propagation times led early observers to make incorrect flare associations for the ^{3}He-rich events.

The case for the association of ^{3}He-rich events with impulsive flares alone was strengthened by evidence that they lacked the characteristics of gradual events and of large proton events. Kahler *et al.* (1985) found that the ^{3}He-rich events showed no evidence of association with CMEs or with metric type II radio emission. Proton events show a strong correlation with both phenomena (see, e.g., Kahler 1982*a*; Kahler *et al.* 1984).

If ^{3}He-rich events are associated with 2–100 keV electron events, then they must also be associated with the kilometric type III radio bursts produced by those electrons. This latter association was observed by Reames and Stone (1986) and was used to extend the list of identified flares. The hard and soft X-ray properties of the events were studied in detail by Reames *et al.* (1988). A composite picture of the X-ray, radio, and particle profiles for a representative event is shown in Figure 5. The lower panel in the figure shows the hard X-ray profiles of the event at high time resolution showing the complex, spiky behavior of an impulsive hard X-ray event. The next panels above compare the hard and soft X-ray profiles. The soft X-ray emission arises from heating of the flare plasma; these measurements were used to derive temperatures in these events. Above the X-ray data are the profiles of three radio frequencies. These profiles and the full kilometric dynamic spectrum in the panel above show the evolution of the type III burst toward lower frequency as the electrons propagate outward from the Sun. Finally, the top three panels show particle observations near 1 AU. The electrons shown are nearly relativistic and are seen to arrive within minutes of the flare. The ^{3}He and ^{4}He are observed at lower energy and arrive in order of $1/v$ as described above. The event we have described occurs within a sequence of four events from the same active region. The onsets of the events are noted by the arrows in the top panels of Figure 5.

An interesting feature of these studies of ^{3}He-rich flares is the observation of a weak but statistically significant anticorrelation between the ^{3}He/^{4}He ratio and any measure of the intensity of the radio or X-ray event (Reames *et al.* 1988). Plots of the ^{3}He/^{4}He ratio versus 2 MHz antenna temperature, the soft X-ray peak flux, and the integral count of hard X-rays are shown in Figure 6. This behavior is similar to the decrease in ^{3}He/^{4}He with increasing proton intensity, reported in early work (see Ramaty *et al.* 1980). It should also be noted that some events with large ^{3}He/^{4}He have no X-ray increase, although all events appear to have kilometric type III bursts.

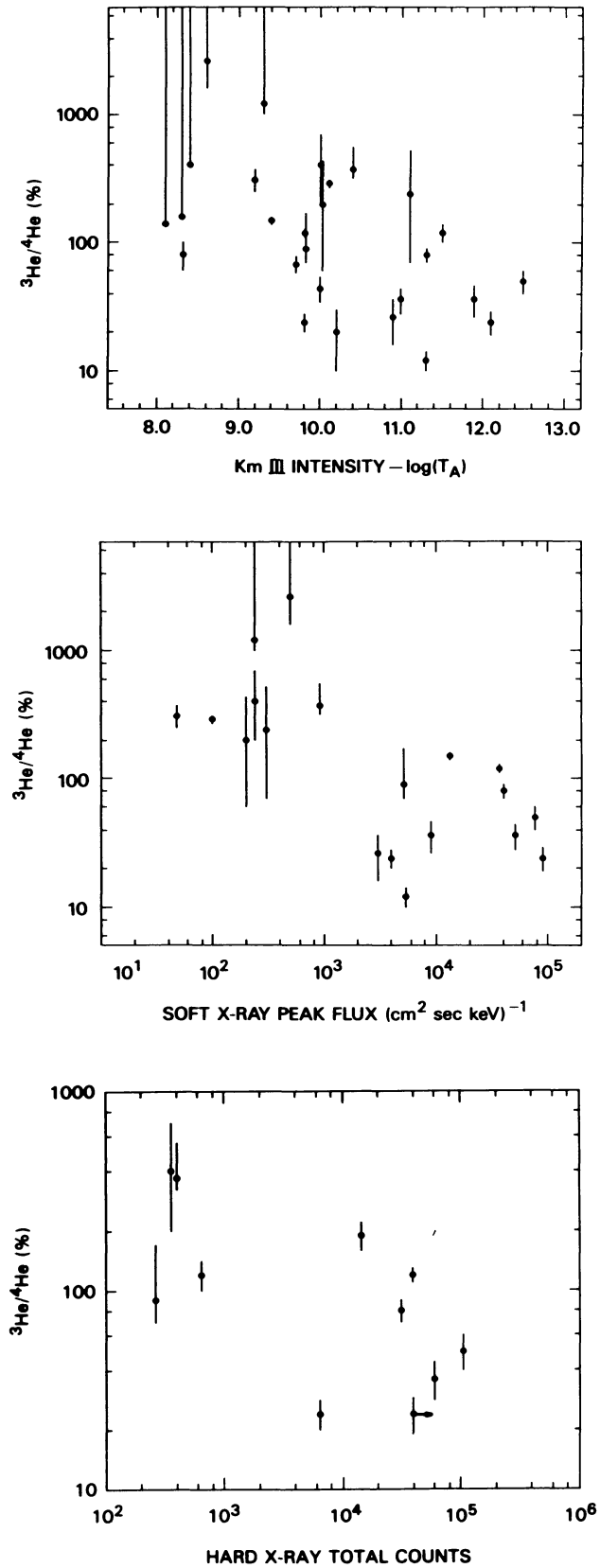

FIG. 6.—Correlation plots of the ^{3}He/^{4}He ratio as a function of the radio, soft X-ray, and hard X-ray intensities in the parent flare. (After Reames *et al.* 1988.)

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Kahler *et al.* (1987) examined the Hα characteristics of ^{3}He-rich events and found that, apart from the smaller size and duration, the events had few distinguishing characteristics. These authors interpreted the lack of Hα and X-ray emission and the lack of a rollover in the electron spectrum down to 2 keV as evidence that the acceleration occurs relatively high in the corona ($> 1.4 \times 10^5$ km).

Our growing understanding of the impulsive flares associated with ^{3}He-rich events, however, increasingly begs the question whether these events are representative of all impulsive flares or whether they are a unique subset in which unusual conditions prevail. The study of the events themselves provides some evidence on this question. First, the frequency of observation of these events has increased with the sensitivity of the observing instruments (Reames and von Rosenvinge 1983; see also event list in Kahler *et al.* 1985 or Mason *et al.* 1986). Second, a direct search for ^{3}He in nonrelativistic electron events (Reames and Lin 1985) showed that events with increasingly high fluxes of 20 keV electrons had an increasingly high probability (up to 68%) of observable ^{3}He. Third, the radio and X-ray events associated with the ^{3}He-rich events are not unusual; they span the full range of parameters typical of impulsive flares. Finally, the recent ^{3}He observations at low energies detect only those events with ^{3}He/^{4}He > 0.1. This already requires an enhancement factor of > 250 for the event to be classified as ^{3}He-rich. We will return to the latter point in the next section.

Early observers (the author included) thought that ^{3}He-rich events were a rare phenomenon, and they wanted to estimate the probability of occurrence of the phenomenon. Searches were made for small impulsive events with proton or ^{4}He time-intensity profiles that resembled those in ^{3}He-rich events, but without any enhancement in the ^{3}He/^{4}He (or Fe/O) ratio. No clear examples of this type of event have been reported in the literature. As far as we know, all of the small impulsive particle events have abundance enhancements.

IV. HEAVY-ELEMENT ABUNDANCES

The question of heavy-element abundances in impulsive flares has two observational aspects. First, there are the extensive studies of the heavy-element abundances in known ^{3}He-rich events. Second, there are recent surveys of heavy-element abundances covering time periods of many years. The latter studies tell us about the frequency and completeness of the abundance measurements. We consider the two types of observations consecutively in the next two subsections.

a) Element Abundances and Ionization States in ^{3}He-rich Events

Events with enhanced abundances of ^{3}He were also found to have enhanced abundances of heavier elements up through Fe (Hurford *et al.* 1975; Hovestadt *et al.* 1975; Gloeckler *et al.* 1975; Anglin, Dietrich, and Simpson 1977; Zwickl *et al.* 1978; McGuire, von Rosenvinge, and McDonald 1979; Mason *et al.* 1980; Reames and von Rosenvinge 1981; see Mason 1987). As stated previously, these enhancements were originally understood theoretically in terms of the partially stripped ions interacting through the second harmonic of their gyrofrequency with waves of the same frequency that were preferentially heating the ^{3}He (Fisk 1978).

While heavy-element enhancements were usually seen in ^{3}He-rich events, the association was incomplete, and a quantitative relationship between enhancements in heavy elements and in ^{3}He was elusive. The status of this situation was summarized recently by Mason *et al.* (1986). These authors examined the distribution of enhancements of each element for an ensemble of ^{3}He-rich events and plotted ensemble average enhancement and the width of the distribution for each species as shown in Figure 7. However, there appeared to be no meaningful correlation between the ^{3}He/^{4}He ratio and any of the element abundance ratios on an event-by-event basis.

A key to the understanding of this lack of correlation, and, in fact, a key to the association of the particles with impulsive flares, lay in the measurements of charge states of the heavy ions (Klecker *et al.* 1984; Luhn *et al.* 1987). The instrument that made these difficult measurements was not sufficiently sensitive to study individual ^{3}He-rich events, so ions were collected during many ^{3}He-rich periods. The charge distributions of Si and Fe during these ^{3}He-rich periods are compared in Figure 8 with the corresponding distributions in a large proton event. The ionic charge states found during the large proton event are typical of those in the ambient corona as observed by measurements in the solar wind. The substantially higher charge states found in the ^{3}He-rich events reveal material that has been processed to high temperature

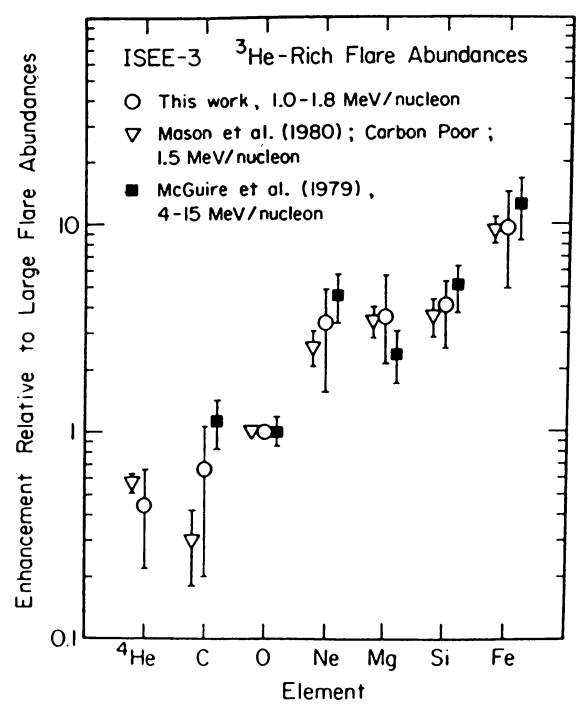

FIG. 7.—Average enhancement of various elements in ^{3}He-rich events relative to their abundance in large proton events. The error bars on the points labeled with open circles indicate the event-to-event variation, not the error in the mean. (After Mason *et al.* 1986. "This work" refers to Mason *et al.*, not to the present paper.)

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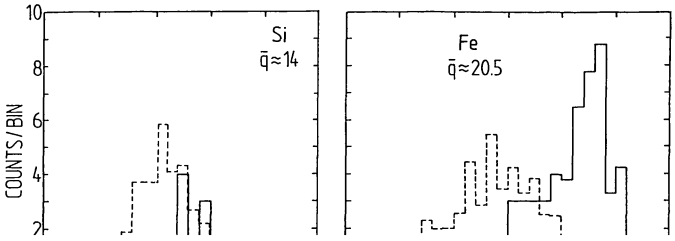

were found in the study of ^{3}He-rich flares (Reames *et al.* 1988), Reames (1988*a*) plotted element abundances as a function of temperature as shown in Figure 9. Six of the nine abundances in Figure 9 do indeed show a statistically significant correlation with characteristic temperature of the event. This additional variation of the abundance ratios with temperature could mask any correlation of the element abundance ratios with the ^{3}He/^{4}He ratio and thus could explain

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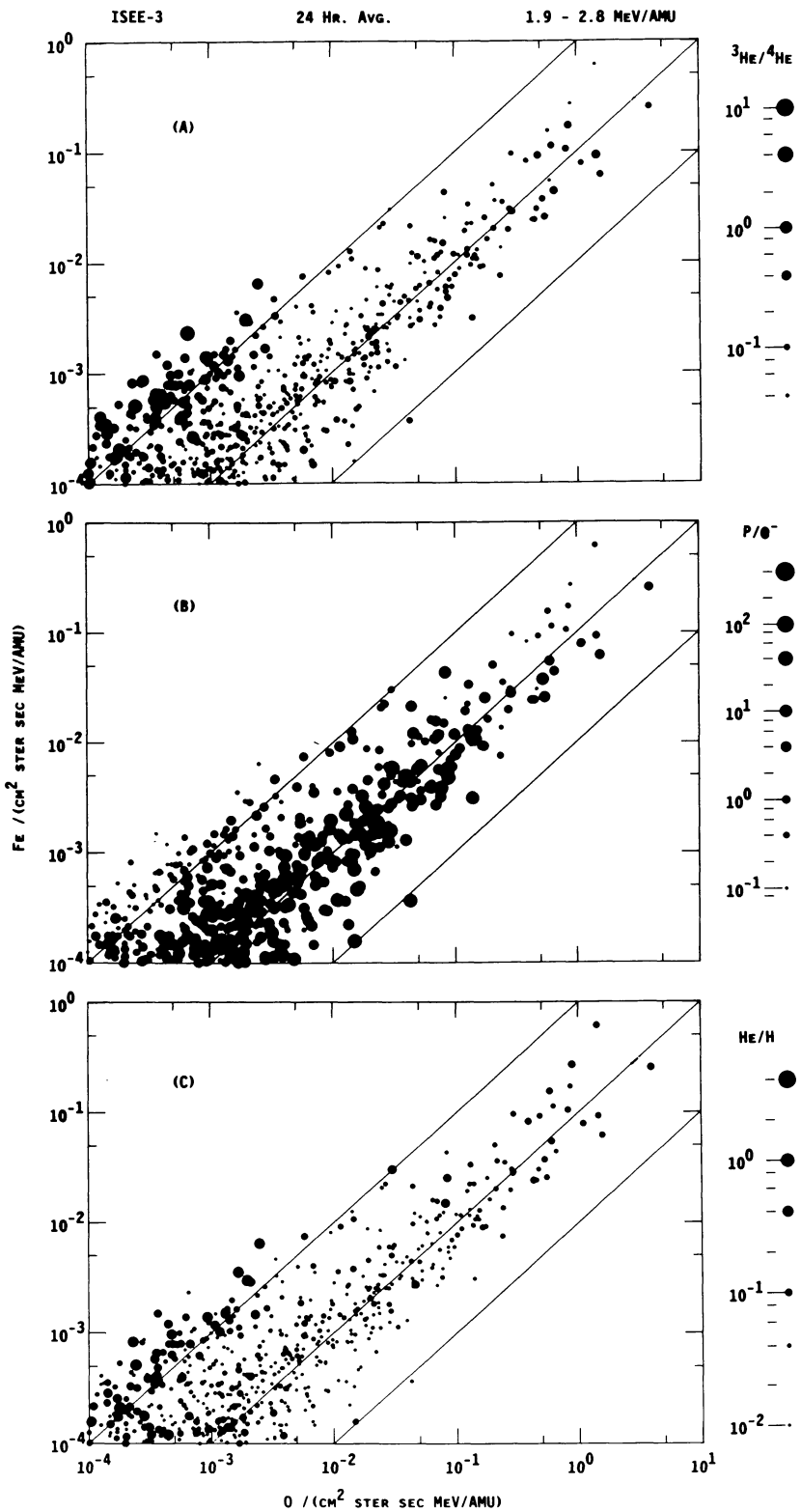

FIG. 10.—Each panel shows the daily averaged intensity of iron vs. that of oxygen for all days with sufficiently large intensities during an 8.5 year synoptic study. The symbol size at each point varies with the value of the parameter shown to the right of the plot. The parameters are (*a*) the ^{3}He/^{4}He ratio, (*b*) the proton/electron ratio, and (*c*) the He/H ratio. These parameters highlight the differences of two populations of particle events. (After Reames 1988*b*.)

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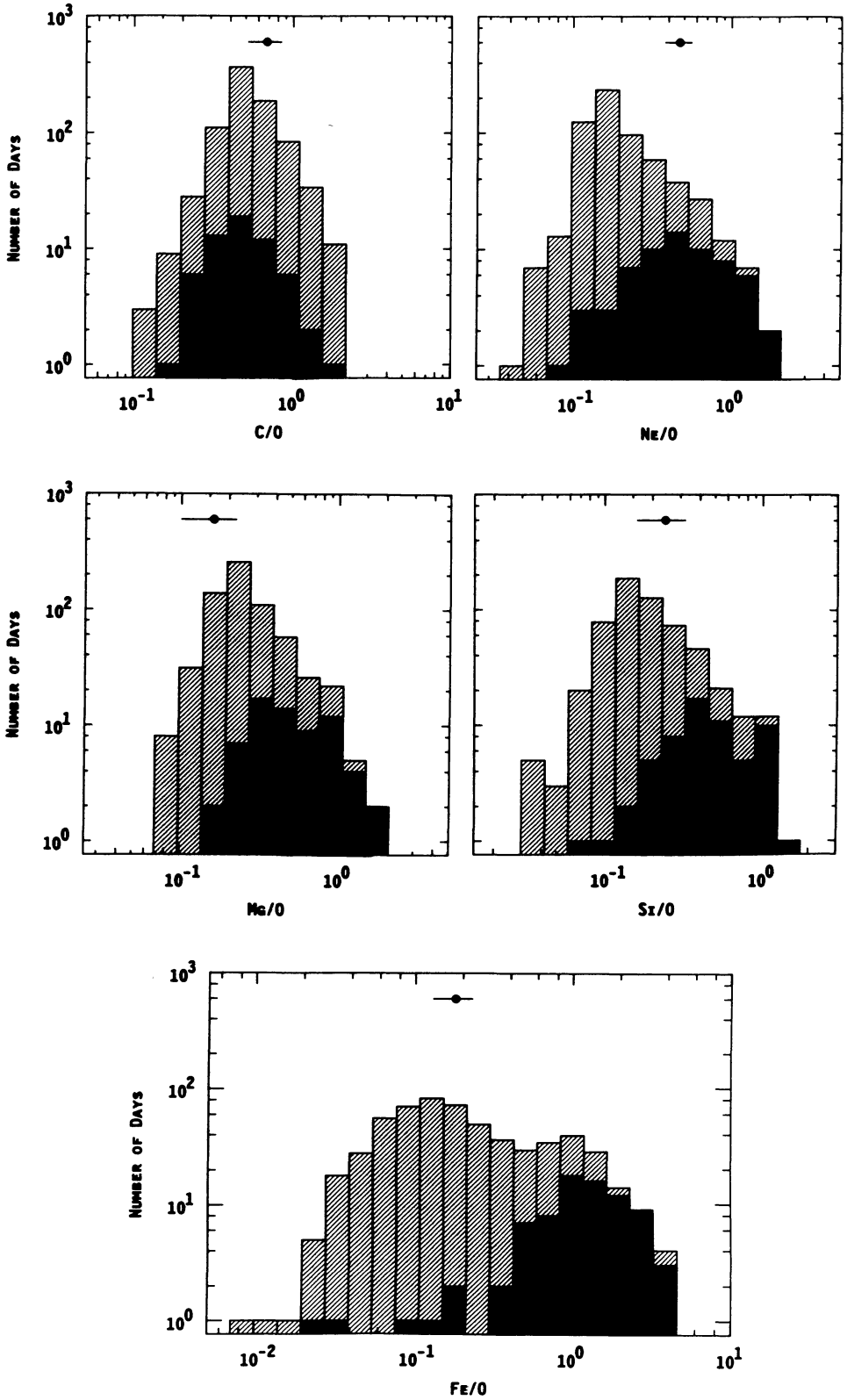

FIG. 11.—Histograms showing the distribution in frequency of occurrence of various particle abundance ratios in the daily-average measurements during the 8.5 year synoptic study. The blackened regions of the histograms are the subset of days when $^3He/^4He > 0.1$. The filled circle near the top of each histogram shows the value of the ratio derived in a GRL flare. (After Reames, Ramaty, and von Rosenvinge 1988.)

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b) Synoptic Abundance Studies

The process of resolving individual SEP events and associating them with the parent flares is subject to a number of limitations. Events that are closely spaced in time are difficult to resolve. Certain features of the composition, size, or time profile of an event may make it easier to resolve, thereby introducing biases in the sample of events. A crude but even-handed way to avoid such biases is simply to divide the particle observations into equal intervals of time and to treat this ensemble of time intervals as if they were separate events. Synoptic studies of this kind make it possible to estimate the frequency of occurrence of SEP events with various properties. The obvious disadvantage of this technique is that it can blend the properties of multiple events that occur in a single interval and can overrepresent the properties of events that persist for several intervals. A time interval of one day is commonly chosen in an effort to balance these conflicting requirements. The results do not depend strongly on the choice of averaging interval.

The first study of this kind was reported by Mason *et al.* (1980). These authors were able to study the element abundances in ^{3}He-rich events in the context of the overall distribution of abundances during a 4 year period. Unfortunately, the period of observation occurred during solar minimum so that impulsive flares were not numerous.

A more recent study (Reames 1988*b*; Reames, Ramaty, and von Rosenvinge 1988) involved an 8 year period from 1978 to 1987 and included the last solar maximum. A significant result of this study was the observation of a bimodal distribution in the Fe/O abundance ratio with the separate contributions of the impulsive and gradual events being evident (Reames 1988*b*). Figure 10 shows the distribution of Fe and O intensities and its correlation with other features of the particle composition. Each panel of the figure shows points representing the Fe intensity versus the O intensity for each day that the intensities exceed minimum values. The size of the symbol at a point varies with a third parameter as shown to the right of the panel. The points in Figure 10 appear to cluster in two groups, roughly along the diagonal lines representing Fe/O = 1.0 and Fe/O = 0.1. The points in the two groups have very different values of ^{3}He/^{4}He, p/e, and He/H. Following our previous discussion of ^{3}He-rich events, it is not surprising to find a ^{3}He-rich, Fe-rich, proton-poor population of energetic particles. This time, however, we find that population in a significant fraction of the observations in an 8 year period.

The distributions of abundances of other elements in the same study are shown in Figure 11. The blackened region of each histogram shows the subset of the distribution for which ^{3}He/^{4}He > 0.1. The progression of increasing enhancement of the ^{3}He-rich component with increasingly heavy elements in Figure 11 is similar to that shown in Figure 7. However, the widths of the distributions for both the enhanced and the unenhanced populations can be seen in Figure 11. Variations in flare temperature undoubtedly contribute to the width of the former, but the cause of the large variation in the abundances of the unenhanced population is not clear.

Of approximately 3000 days of observation, about 600 days have sufficient particle intensities to contribute to the plots in Figures 10 and 11. Of the 600 days contributing to the Fe/O distribution in Figure 11, 163 (27%) have Fe/O > 0.5. Many of the time periods that contribute to the abundances near Fe/O = 0.1 contain large proton events each of which lasts for many days. These events are overrepresented in the plot. In contrast, the days on which Fe/O > 0.5 often contain many small impulsive events. These events are underrepresented in the plot. Considering events rather than days, it is likely that most events have Fe/O > 0.5.

An example of a time period with many impulsive events is given in Figure 12, which shows particle data from the Goddard experiment on the *ISEE 3* spacecraft (von Rosenvinge *et al.* 1978). The individual increases are best seen in the 0.22–2.0 MeV electron data. These electrons are nearly relativistic and, hence, arrive within minutes of the flares that are indicated by their Hα coordinates in the figure. Intensities of 2–3 MeV amu^{-1} Fe are also shown. O intensities are not shown; however, Fe/O > 1.0 in every 2 hr averaged period for which an Fe intensity is plotted. Fe increases can be seen in association with the first and last events in Figure 12. The Fe arrives several hours after the associated electrons because of the velocity dispersion, but the profiles of the Fe are nearly as impulsive as those of the

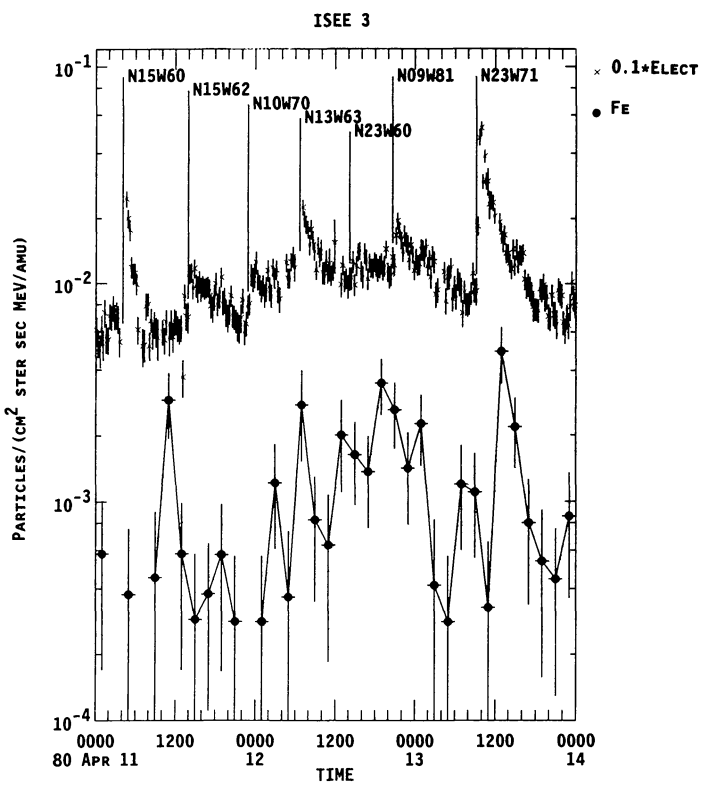

FIG. 12.—Example of a period of time contributing high values of Fe/O in the synoptic study. The intensity of 0.22–2 MeV electrons (×0.1) is shown at the top with flare coordinates labeling several increases that occur during the 3 day period. Intensities of 2–3 MeV amu^{-1} Fe are shown below. Prominent peaks in the Fe correspond to those in electrons and have similar profiles, but are delayed by the velocity dispersion. Fe/O ≥ 1.0 for every interval shown. There are no increases in protons (not shown) during this time period, but the events are not measurably ^{3}He-rich either.

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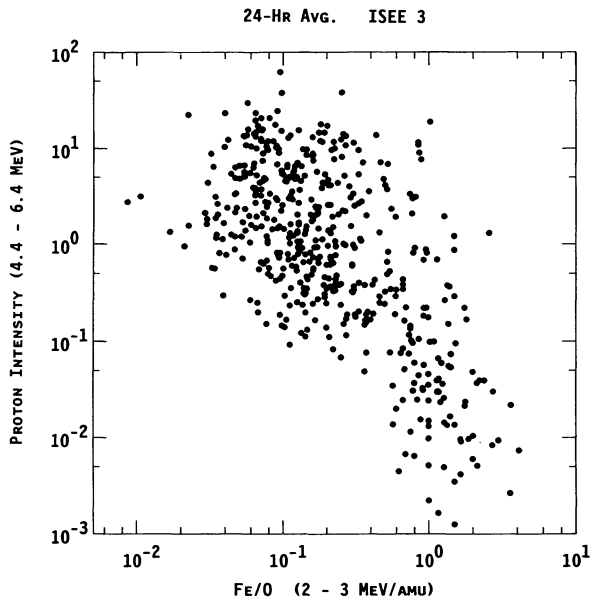

FIG. 13.—Scatter plot of the proton intensity vs. Fe/O in the synoptic study. Only events with large proton intensities have low unenhanced abundances of Fe. Events with low proton intensities *always* show Fe enhancements.

electrons. For the remainder of the events in Figure 12 the individual increases in Fe cannot be resolved because of poor statistics, but the effect of multiple increases is apparent. None of the events in Figure 12 were ^{3}He-rich by the usual criterion, since $^3\mathrm{He}/^4\mathrm{He} < 0.1$; however, ^{3}He could be enhanced relative to its coronal abundance by a considerable amount without being detectable.

A final plot from the synoptic abundance study is shown in Figure 13, where the daily averaged intensity of 4.6–6.4 MeV protons is shown as a function of the Fe/O ratio on that day. Figure 13 shows a strong inverse correlation between the proton intensity and the Fe/O ratio. Days with Fe/O < 0.5 are all associated with large proton intensities, while days with an average intensity of < 0.1 protons (cm^2 sr s MeV)$^{-1}$ all have Fe/O > 0.5. There is a tendency for the points to cluster in two regions of Figure 13.

V. GAMMA-RAY LINE EVENTS

The observation of γ-ray lines in impulsive flares (see review by Chupp 1984) has brought a new opportunity for studying particle acceleration and element abundances in these flares (see Ramaty, Kozlovsky, and Lingenfelter 1979; Ramaty and Murphy 1987). Gamma-ray lines are produced by the de-excitation of nuclear levels of heavy ions in the flare plasma that are excited in nuclear reactions with energetic particles. Narrow lines from excited states of ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, and ^{56}Fe have been observed, as well as the de-excitation line from deuterium that is formed by neutron capture. These lines are emitted from nuclei at rest; comparable lines from excited nuclei in the energetic particles are Doppler-broadened to the extent that they cannot be individually resolved. These events have been studied extensively but will be discussed here only as they relate to particle observations in space.

The relative intensities of the γ-ray lines depend upon the intensity and spectrum of bombarding particles, and attempts were soon made to compare the number of protons observed in space with that in the flare as deduced from the γ-ray observations (von Rosenvinge, Ramaty, and Reames 1981). More complete comparisons of this kind have been made by Cliver *et al.* (1987) and Kallenrode *et al.* (1987). Despite their intense photon emission at the Sun, the γ-ray events tend to make unimpressive interplanetary proton events; in fact, in the Cliver *et al.* (1987) study, only about 20 events with both γ-ray lines and positive interplanetary proton fluxes were seen in 5 years of observations. Estimates of the number of protons that "escape" into interplanetary space is usually small compared with the number in the flare loop in these events, presumably because the energetic particles are contained in the coronal loops until they plunge into the Sun. Like most impulsive events, γ-ray line events are dominated by electrons (Evenson *et al.* 1984) in interplanetary space.

Gamma-ray lines are presently observable only in relatively large events, and about 75% of these events have associated type II radio emission, indicating the presence of a coronal shock (Cliver *et al.* 1987). It is possible that the energetic protons inside (and outside) the loop are accelerated by this shock in a second step (Bai 1986) of the impulsive event, but little time is allowed for this mechanism to occur.

The best observations of energetic particles from γ-ray line (GRL) flares were obtained on the *Helios* spacecraft in the events of 1982 June 3 and 1980 June 21 (McDonald and Van Hollebeke 1985). Both of these flares showed high e/p ratios, $^3\mathrm{He}/^4\mathrm{He}$ ratios of a few percent, and Fe/O ratios of 2.5 ± 0.5 and 0.91 ± 0.02, respectively (Van Hollebeke, McDonald, and Trainor 1985), the signature of impulsive flares. The 1982 June 3 flare also had a strong second (gradual) phase that may have produced the intense flux of energetic protons in this event.

Stochastic acceleration of protons by gyroresonant collisions with turbulent Alfvén waves has been considered as a means of proton acceleration in flares (Barbosa 1979; Eichler 1979; Möbius *et al.* 1982; Forman, Ramaty, and Zweibel 1986). Recently, Miller and Ramaty (1987) have modeled the proton and electron acceleration in GRL flares to produce the observed photon spectrum using a stochastic acceleration model involving scattering of the protons by a Kolmogorov, $k^{-5/3}$, spectrum of Alfvén waves, and scattering of electrons by a $k^{-7/3}$ spectrum of whistler waves, where k is the wavenumber.

Ramaty *et al.* (1988) have modeled the magnetic configuration of a flare loop and the density variation of the solar atmosphere and have performed Monte Carlo calculations of particle trajectories along the loop in the presence of wave scattering. The particles undergo pitch-angle scattering into the loss cone, so that they plunge into the chromosphere. The altitude and angular distributions of photon emission and their time profile are calculated in this model. These authors found curvature drift to be the primary means of

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particle escape from the loop. The time to escape by this mechanism depends upon the particle mass m and velocity β as $1/(m\beta^2\gamma)$, so that only highly relativistic ions escape easily, while most are scattered into the loss cone.

Another aspect of the GRL events is that the line intensities depend upon the abundances of nuclei in the ambient flare plasma. This provides us the potential to compare the abundances in the interplanetary particles directly with those in the flare site. As yet this potential has not been realized, since GRL–derived abundances are available for only one event in which SEP abundances could not be measured. However, a preliminary comparison of the GRL abundances with the overall SEP distribution has shown that an interesting correspondence in the neon abundance of the GRL event and that found in ^{3}He-rich events (Reames, Ramaty, and von Rosenvinge 1988). This can be seen in Figure 11, where the GRL abundances are plotted as a solid circle with an error bar at the top of each panel. The Ne abundance in ^{3}He-rich events does not appear to vary with temperature (see Fig. 9), yet it appears to be enhanced relative to the coronal abundances as measured in large proton events (shown as dashed lines in Fig. 9) and in the solar wind (Bochsler, Geiss, and Kunz 1986). Note that Ne also lies above the trend line of element enhancements in Figure 2.

Because of the high value of its first ionization potential (FIP), Ne occupies a special place in theories that describe differences in element abundances between the photosphere and the corona (see Meyer 1985*a*, *b*). The abundances of elements with a FIP ≥ 9 eV (corresponding to $T \sim 10^5$ K) appear to be suppressed by a factor of about 4 in the corona. As material is transported from the photosphere to the corona, elements with a FIP above ~ 9 eV are believed to remain neutral, while those with low FIP are ionized. Less efficient transport of neutral ions leads to a suppression of the high–FIP elements (see review in Meyer 1985*b*). These FIP–dependent effects are very different from the Q/A dependences in the large-flare SEP abundance variations, for example. The large enhancement of only Ne in GRL observations and in ^{3}He-rich events suggests either that the photospheric abundance of Ne is extremely high or that the FIP model requires modification. In any case the origin of the material involved is in question. At present, the observations are only a preliminary hint at some interesting underlying questions.

It is especially important that GRL abundances be determined for as many flares as possible to study the extent of flare-to-flare variations in these values. If the variations in the GRL abundances are small, than the large variations in both the large-flare SEP abundances and the solar wind abundances represent biases in the manner in which the particles are selected or accelerated rather than real fluctuations in the coronal abundances. The existence of multiple abundance measurements in the Sun gives us the ability to distinguish the separate mechanisms that lead to abundance differences between the photosphere, the corona, and the particles in interplanetary space. These same mechanisms may affect the abundances in distant astrophysical objects where our ability to measure and understand them is much more limited. In planetary nebulae, for example, variations in Ne/O also occur and are attributed to different nucleosynthetic mechanisms (Aller and Keyes 1987); the possibility that plasma enhancement mechanisms operate in such cases merits consideration.

VI. AN ACCELERATION MODEL

While several mechanisms have been proposed for accelerating the unique particle abundances of energetic particles, such as ^{3}He or Fe enhancements that we observe from impulsive flares, little attention has been paid to a model that would relate those mechanisms to the temporal and spatial features of the flare. Particles that are preferentially heated must be subjected to an unspecified acceleration mechanism and then escape with an unspecified efficiency from the acceleration region. The problem of escape is especially acute for the nonrelativistic electrons observed in all impulsive flare events because of their inability to cross magnetic field lines. As an illustration of this point, the formula for escape from a flare loop by curvature drift given by Ramaty *et al.* (1988) gives an escape time of 0.5 yr for a 2 keV electron; these electrons have gyroradii of only about 1 cm in a 100 G magnetic field. Scattering in the loop is more likely to cause electrons to precipitate than to hasten their escape. For ions at 1 MeV amu^{-1} this escape time would be reduced to 4 hours. However, such long escape times are inconsistent with the observed time profiles in impulsive events. It should also be noted that most of the impulsive flares are not accompanied by CMEs; thus there is no evidence of field line rearrangements that could free trapped particles.

Faced with the extreme difficulty of getting low-energy electrons out of loops rapidly enough to produce type III bursts, Sprangle and Vlahos (1983) studied a mechanism in which electromagnetic waves emitted by electron beams in

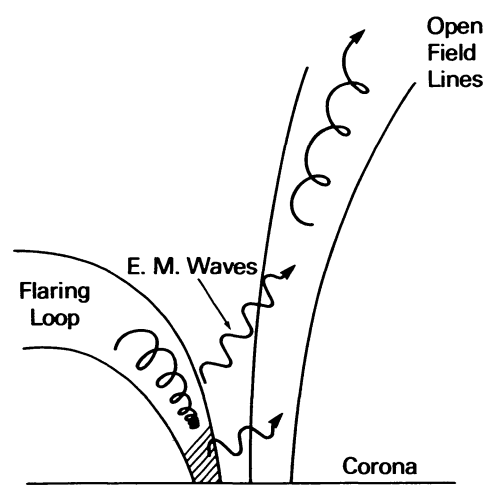

FIG. 14.—Diagram showing the probable mechanism of particle acceleration in all but the largest impulsive flares. Waves generated by particle beams in the flare loop propagate outward to open field lines, where they accelerate electrons by a resonance mechanism such as that described by Sprangle and Vlahos (1983). In many events lower frequency waves are sufficiently intense to accelerate ions stochastically in the same region of open field lines.

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the flaring loop propagate out of that loop to accelerate electrons on open field lines nearby as shown in Figure 14. This calculation has been extended recently by Karimabadi *et al.* (1987). The mechanism involves trapping of electrons in the wave field of nearly circularly polarized electron cyclotron waves propagating along the magnetic field. It results in highly resonant energy transfer with a bandwidth of the radiation of about 1% and a transfer time of less than a second, as is required by observations of near-synchronism between the onsets of the hard X-ray emission and type III bursts.

It is interesting to consider the possibility that ion acceleration in impulsive events also occurs outside the loop in a topology similar to that shown in Figure 14. For the sake of illustration, suppose that a uniform spectrum of waves emerges from the region near the base of the flaring loop with sufficient energy density to cause stochastic acceleration of ions. In the absence of wave absorption, the energy density would fall off with distance as the waves spread over an increasingly large volume. Any particular ion species would be most strongly scattered by waves with a frequency near its gyrofrequency. Suppose further that high-frequency electromagnetic and plasma waves simultaneously radiate outward to heat the electrons that further ionize the heavy elements in the surrounding material.

As our fictional spectrum of waves emerges from the flare region, the waves begin to be absorbed by the local plasma as their energy is transferred to ions. Waves near the proton gyrofrequency (and its harmonics) are absorbed first because of the high abundance of protons. Waves near the ^{4}He gyrofrequency continue to accelerate ^{4}He over a larger spatial distance from the flare before they are sufficiently attenuated. Species such as ^{3}He and heavy ions with low abundances and well-separated gyrofrequencies are preferentially accelerated farther from the flare or at higher altitudes where open field lines are more probable. In larger, more intense flares proton and ^{4}He acceleration would occur farther out from the flare, decreasing the magnitude of the enhancement as is seen in Figure 6.

Notice that high-frequency waves such as whistler waves that interact with electrons propagate faster than the low-frequency waves that resonate with ions, hence the electron temperature could be raised and the heavy nuclei could be further ionized before the arrival of the waves that resonate with the ions. The latter waves propagate at speeds near the ion sound speed, which is about 300 km s^{-1} for an electron temperature of 10^7 K or 1 keV.

This qualitative model with a uniform frequency spectrum of waves is not adequate to predict the observed particle abundances from impulsive flares. However, it does furnish an example of a straightforward way in which enhancements of rare species could occur, and the consequences of the model may be superposed upon the consequences of the actual wave-frequency spectrum from the flare.

The actual spectrum of waves involved in the acceleration of ions may be quite complex. In addition to EIC waves near the gyrofrequencies of the dominant particles (Fisk 1978; Varvoglis and Papadopoulos 1983), lower hybrid waves may be generated between the gyrofrequencies of electrons and protons and have been suggested for acceleration in ^{3}He-rich flares (Ramadurai and Thejappa 1986). This wave spectrum could be broadened by magnetic field variations throughout the emission region. Preheated particles could be further accelerated stochastically by waves with frequencies far from gyroresonance (Abe *et al.* 1980, for example, consider $2 \leq \omega / \Omega \leq 20$) or by Alfvén waves (Barbosa 1979; Möbius *et al.* 1982).

Alfvén waves have frequencies ω that are small compared with Ω. These waves only resonate with particles whose velocity is larger than the Alfvén velocity. For a magnetic field of 50 G and a density of 10^9 cm^{-3}, the Alfvén velocity is 3500 km s^{-1}, corresponding to particles with about 65 keV amu^{-1}.

Note that the low-frequency waves, even electromagnetic waves, that exist near the flare cannot be observed at Earth, since they cannot escape the solar atmosphere. At some higher altitude the waves would encounter a region where their frequency was equal to the local electron plasma frequency and they would be absorbed. This means that only the energetic ions themselves carry information on the waves that caused their enhancement.

Nevertheless, it seems plausible that the energetic ions observed to emerge from impulsive flares are accelerated on open field lines by stochastic interactions with plasma waves arising from the nearby flare. When there is sufficient wave energy for acceleration, the particles scatter often and thus are contained by "diffusive mirroring" until the waves dissipate (see Miller and Ramaty 1987; Forman, Ramaty, and Zweibel 1986). While the acceleration of the electrons is topologically similar, there need be no simple relationship between their intensity and that of the ions. Conditions of geometry, temperature, and wave spectrum may be favorable for ion acceleration in only a fraction of the events with type III bursts. It should be noted, however, that there is at present no quantitative explanation of the typical abundance enhancements seen in Figure 7.

In more energetic events, direct stochastic proton acceleration might occur on open field lines and protons and other nuclei above about 20 MeV amu^{-1} might leak from the loop by curvature drift in a time scale of 20 minutes or less. The early time profile of particles from stochastic acceleration might appear to be "diffusive," since the particles escape from the wave containment region by diffusion while the waves persist. In events that are sufficiently large to produce coronal shocks, as observed via type II radio emission, particles undoubtedly undergo additional acceleration, and their history may become quite complex.

Miller and Ramaty (1987) estimate that stochastic acceleration occurs wherever the wave energy density exceeds 1 erg cm^{-3}. For a plasma temperature of 1 keV, a density of 10^9 cm^{-3}, and a magnetic field of 100 G, the thermal and magnetic energies are 3 and 400 ergs cm^{-3}, respectively. Under these conditions a magnetic loop should be stable against disruption, and stochastic acceleration could proceed throughout the volume where the wave energy remained sufficiently high. If acceleration outside closed loops is to dominate the observed particle population, then sufficient energy in Alfvén waves, for example, must be generated to

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allow more than 1 erg cm^{-3} over a volume somewhat larger than that of the loop, without reaching levels that are comparable to the energy density in the magnetic field.

The unique abundances in the particles from impulsive flares allow an experimental test for differences in the abundances inside the outside the flare loop by obtaining SEP and GRL observations in the same event. If the ions accelerated inside the loop had high $^3He/^4He$ and He/H ratios, then γ-ray lines from the de-excitation of ^6Li (3.56 MeV), ^7Li (0.478 MeV), and ^7Be (0.431 and 0.478 MeV) would be strongly enhanced (see Ramaty, Kozlovsky, and Lingenfelter 1979). These lines are produced by reactions such as $^4He(\alpha, n)^7Be^*$, $^4He(\alpha, p)^7Li^*$, $^4He(\alpha, n)^7Be(\varepsilon)^7Li$, $^4He(\alpha, pn)^6Li^*$, and $^4He(^3He, p)^6Li^*$. All of these reactions involve He beams. In large proton events H/He can be greater than 100, while in ^{3}He-rich events H/He can be less than 1. If the "beam" inside a flaring loop is mostly He, the lines of Li and Be could be excited with an intensity comparable to those from excited states of C and O. If the "beam" is nearly all H, lines of Li and Be would be negligible compared with those from C and O Observation of the strong lines from the de-excitation of Li and Be would suggest that particles with enhanced abundances are accelerated in the loop. Observation of lines that reflect normal coronal abundances together with energetic particles in space with enhanced abundances would suggest that different mechanisms accelerate particles inside and outside of the loops. Lines from Li and Be isotopes have not yet been observed.

In the large GRL events the nuclear reactions that lead to nuclear excitation also lead to production of secondaries, such as deuterium and tritium. Some of these secondaries would propagate upward into the coronal loop, especially for the interaction of particles near their minimum mirroring altitude. The extent of this secondary contribution could be estimated from the same loop transport models used to calculate neutron and γ-ray production. If the particles in space leaked from the loop, they would be expected to be contaminated by such secondaries. Particles accelerated outside the loops would have little chance to produce secondaries. It is not clear whether the current observed upper limits on secondaries represent a constraint on particle escape from loops.

VII. SUMMARY AND CONCLUSIONS

We began by noting the very large number of impulsive flares that occur on the Sun. Type III radio bursts frequently accompany those flares, indicating that electrons are accelerated onto open field lines and propagate away from the Sun. Whenever an observer at 1 AU is within about $\pm 25°$ of the central field line to the flare, 2–100 keV electrons are observed to arrive in a simple velocity-dependent order from these events. With the present instrument sensitivity, we observe ions above 1 MeV amu^{-1} in about 25% of these events. The ions invariably show anomalous abundances typified by high values of the $^3He/^4He$, Fe/O, He/H, and e/p ratios when compared with the corresponding values in large flares, in the solar wind, or in spectroscopic measurements of the photosphere or corona.

Early observers thought that ^{3}He-rich events were rare, and they searched for similar small impulsive events that did not have enhancements in $^3He/^4He$ or Fe/O. Such events have not been found. Thus we have arrived at the position that abundance enhancements are a characteristic feature of the observed interplanetary particles from impulsive flares.

Furthermore, the heavy elements from impulsive flares are highly ionized, and the abundances of many elements show a correlation with the soft X-ray temperature of the flares. Evidently the energetic particles we observe are drawn from material that has been heated in the flare. In fact, these abundance anomalies may serve as a signature of this flare-heated or first-phase material in larger, more complicated events.

In contrast, the large proton events typically show element abundances and ionization states that are similar to those in the corona and the solar wind. The particles from these events are consistent with acceleration of ambient coronal material by a shock, for example. These events are associated with CMEs and type II and IV radio bursts and gradual X-ray bursts, and they often lack an impulsive flare or type III radio burst. We have not discussed events of this class except to distinguish them from impulsive flare events.

It seems likely that the energetic particles that we observe from impulsive solar flares are accelerated on open field lines near the flare where particles are preferentially heated by resonant absorption of plasma waves near their gyrofrequencies and subsequently accelerated stochastically by low-frequency waves such as Alfvén waves. The waves are driven by particle beams and by turbulence in the core of the flare. The requirement for an open-field acceleration mechanism is driven by the extreme difficulty in removing low-energy electrons and ions from flare loops on a fast time scale and by the lack of shock waves and CMEs in small events. In addition, this configuration increases the probability of enhancing rare species whose gyrofrequencies differ from those of the dominant species. This hypothesis may be tested by comparing GRL and SEP observations in the same event to see whether de-excitation lines of Li and Be isotopes accompany ^{3}He-rich events.

The particle abundances in impulsive solar flares provide unique information on wave-particle interactions in the flare plasma that is not available from any other source. Radio emission from flare altitudes can only be observed at frequencies that are orders of magnitude higher than those of interest here. Generally, the smaller events will provide maximum information, since they lack the complexity of additional mechanisms associated with shocks and CMEs.

Comparison of the SEP abundances of elements with those derived from γ-ray line intensities allows direct comparison of the local ambient abundances with those in the accelerated beam. This allows us to determine which elements are enhanced by the acceleration and which are not. Preliminary comparison of the GRL and SEP abundances shows a Ne abundance that is surprisingly high ($Ne/O \approx 0.4$) in the GRL and impulsive flare particle abundances, suggest-

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ing that the solar abundance of Ne may be at least a factor of 3 higher than previously believed. An understanding of these element abundances in the Sun and of the mechanisms that affect them may aid our understanding of abundance variations observed elsewhere in the Galaxy.

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