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CLASSIFICATION OF SOLAR ENERGETIC PARTICLES

D. Ruffolo

Department of Physics, Chulalongkorn University, Bangkok 10330, THAILAND

ABSTRACT

While it is now common to refer to a solar event as "impulsive" or "gradual," the classification of the event can be difficult in practice and does not completely clarify the characteristics of solar energetic particles. In particular, a single event can produce multiple particle populations with distinct physical properties. We therefore propose to classify solar energetic particle *populations* of a given species, energy range, and time period in terms of their origin and final acceleration sites, i.e., in terms of their acceleration history. The former can be inferred from low-energy ionic charge states, indicating a solar energetic particle origin in the solar wind (*w*), the open field line corona (*c*), or a hot flare loop (*f*), respectively. Presumably the site of origin is also the site of initial stochastic (*f*) or coronal mass ejection-driven shock (*c* or *w*) acceleration. The other dimension of our classification scheme is the final site of (substantial) acceleration, also indicated by *f*, *c*, or *w*. This can frequently be determined by a qualitative examination of the time-intensity or time-energy profile. We demonstrate this classification scheme using publicly available heavy ion data from the Advanced Composition Explorer mission. Distinct types of SEP populations can be identified: *ff* (impulsive), and *cc*, *cw*, and *ww* (gradual). Thus, when the usual classification refers to a gradual event, this fails to distinguish between particle populations of three distinct acceleration histories. By focusing on observational indicators of the acceleration history, this solar energetic particle classification scheme can help to identify outstanding physics questions and facilitate the interpretation of solar energetic particle abundances and spectra.

1. RATIONALE

Solar energetic particle (SEP) observations refer to temporary increases in the cosmic ray flux, which are associated with solar flares (Forbush, 1946) or with interplanetary shocks of solar origin (Bryant et al., 1962). The latter are now known to be driven by coronal mass ejections (CMEs), and the related and frequently associated solar flares and CMEs can collectively be called "solar events" (defined by solar characteristics). In certain contexts it is useful to classify solar events as "impulsive" or "gradual." This idea was developed by many authors over a period of more than a decade, starting with the classification of X-ray flare observations by Pallavicini et al. (1977), with the terms impulsive and gradual referring to the duration of X-ray emission. Various SEP properties have been found to be correlated with the impulsive or gradual nature of the solar event, including:

- a ^{3}He/^{4}He ratio enhanced by up to 10^4 in impulsive events (which for this reason have also been termed "^{3}He-rich events"; Hsieh and Simpson, 1970; Garrard et al., 1973),
- heavy ion enhancements in impulsive events (Hurford et al., 1975),
- a higher electron/proton ratio in impulsive events (Evenson et al., 1984; Cane et al., 1986),
- higher Fe and Si charge states in impulsive events (Klecker et al., 1984; Luhn et al., 1987), and
- a broader heliolongitudinal distribution for gradual events (Cane et al., 1986).

Impulsive events have been suggested to involve stochastic acceleration at the flare site, while there is evidence that the bulk of SEP from gradual events are accelerated at CME-driven shocks (see §2).

However, as measurements have become more detailed, and our knowledge about solar events has improved, some problems have been encountered in classifying the solar event associated with given SEP observations. It is now known that the key physical difference between impulsive and gradual events, with regard to SEP, is that the latter are dominated by a CME-driven shock. In this context, optical and type II/III radio observations can serve as indicators of coronal or interplanetary shock waves and associated particle (though not necessarily SEP) acceleration. When CME/shock structures are observed as they propagate outward from the Sun and impact the observing spacecraft, their absence or presence is the preferred criterion for event classification, and a correlation of SEP and CME/shock properties is highly desirable. In the meantime, one must use other characteristics as proxies. The original classification of Pallavicini et al. (1977) was in terms of properties of flare X-ray emission. However, this is not applicable in cases where SEP are associated with a CME and not with a flare. Furthermore, apparently reasonable flare identifications are not unique. Because of these difficulties, most modern SEP researchers do not base impulsive/gradual characterization on flare or CME criteria, and instead employ criteria based on the SEP themselves.

There are also problems with using SEP criteria for classifying a solar event as impulsive or gradual, and then using the type of event to classify the SEP. In practice, SEP researchers have expressed problems such as disagreement as to whether certain events are impulsive or gradual, an inability to classify events that show some impulsive attributes and some gradual attributes, and the need to refer to some events as "intermediate" or "mixed" (Cohen et al., 1999; Möbius et al. 1999a; von Rosenvinge et al., 1999). Furthermore, it is possible for a single event to produce multiple SEP populations. The best-known example is that what we now call a gradual event can produce two clear peaks in time-intensity profiles: a prompt peak with a harder spectrum (more prominent at higher energies), and a delayed peak with a softer spectrum, coinciding with the arrival of an interplanetary shock associated with that event. These features are well illustrated in Figure 1 (i.e., Figure 18 of Bryant et al., 1962), showing that these features have been known for nearly 40 years. The modern understanding is that in such a gradual event, the CME-driven shock accelerates particles both while it is near the Sun (prompt component) and in the interplanetary medium (delayed component). The different spectra are an example of the distinct physical properties of these components. Another example of different SEP populations from the same event may be provided by energy-dependent SEP charge states, such as those observed in October-November, 1992 (Oetliker et al., 1997). Therefore, the classification of a solar event as impulsive or gradual does not completely clarify the characteristics of the associated SEP themselves.

In fact, what we really want to know about SEP is their acceleration history, first in broad terms regarding ac-

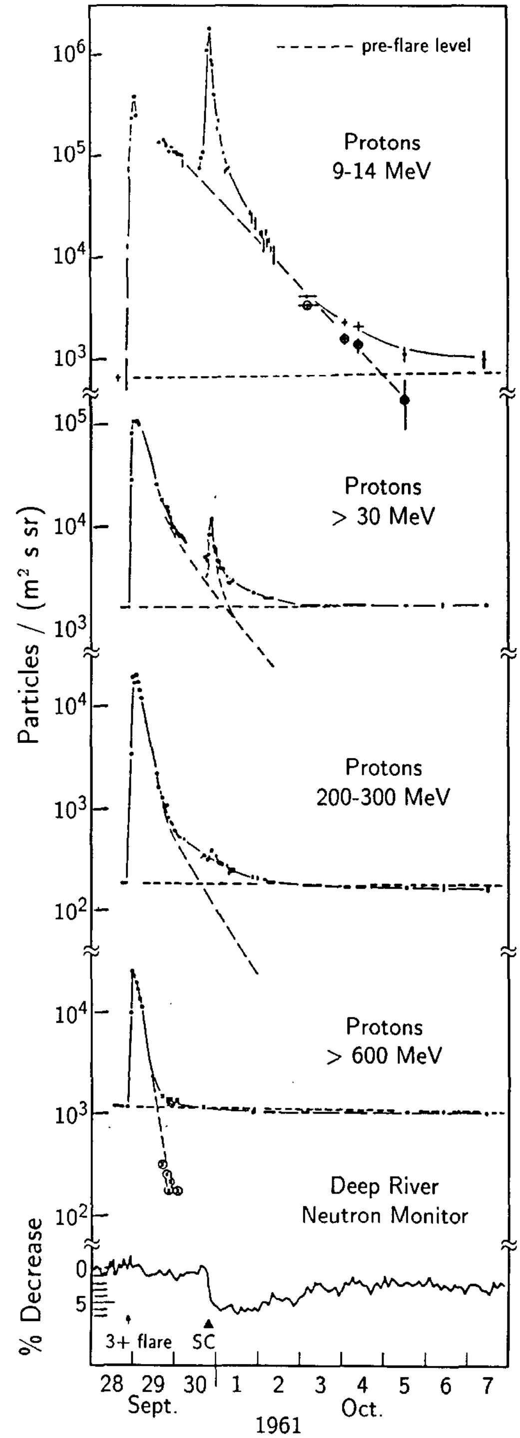

Fig. 1. Representative proton intensities between September 28 and October 7, 1961; the decay of the solar proton event and the arrival of the energetic storm particles late on September 30 are shown. The Deep River neutron monitor record is shown for comparison. [Based on Fig. 18 of Bryant et al. (1962)]

celeration sites, and later in detailed terms regarding the physical conditions and acceleration mechanisms there. The classification of the parent solar event as impulsive or gradual can be helpful by identifying whether a CME-driven shock plays a role, but as discussed above, a single event can give rise to multiple observed SEP *populations* from different acceleration sites. Therefore, in this work we propose to classify observed SEP populations of a given species, energy range, and time period in terms of their initial and final acceleration sites. We argue that the initial acceleration site, i.e., site of origin, of heavy SEP ions can be inferred from their charge states, and the final acceleration site can usually be determined from a qualitative examination of the time-intensity profile. It is proposed that this classification scheme can provide an improved basis for comparison of SEP *populations*, i.e., to compare/contrast SEP composition and spectra with the same/different acceleration histories, and also to identify outstanding physics questions for further work.

2. CLASSIFICATION SCHEME

We propose to classify observed SEP populations of a given species, energy range, and time period in terms of their acceleration history, i.e.,

- the site of origin, which can also be called the initial acceleration site or the seed population, and
- the site of final (substantial) acceleration.

Useful indicators of these sites are

- ionic charge states, and
- time-intensity profiles,

respectively, as we shall discuss shortly. Once the acceleration history is indicated in this manner, one can proceed to examine the elemental and isotopic composition and spectra emerging from these acceleration sites. Note that this classification requires only SEP measurements, which is considered desirable in the SEP research community.

During solar events, there is evidence that particles can be accelerated at three sites, *f*, *c*, and *w* (Figure 2):

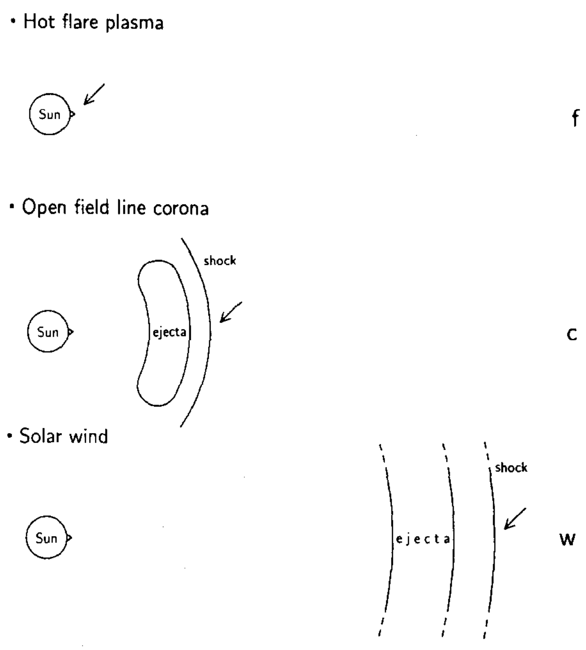

Fig. 2. Illustration of sites of SEP origin or final acceleration.

f - Hot flare plasma. Evidence comes from the dramatic enhancements in the $^3He/^4He$ ratio in many impulsive events, best explained by resonant acceleration by magnetohydrodynamic waves (Fisk, 1978; Temerin and Roth, 1992; Miller and Viñas, 1993) in a region of high energy density. Further, direct evidence of a high-temperature source is provided by ionic charge states (§4).

c - Shocks while propagating in the outer corona, i.e., near the Sun. There are several lines of evidence favoring distributed acceleration at a broad shock front during gradual events, with SEP rapidly escaping along open field lines (Mason et al., 1984; Lee and Ryan, 1986; Reames, 1990; Ruffolo, 1997). Acceleration near the Sun is necessary to explain prompt SEP components from gradual events (see Figure 1), which can be observed before the shock would have had time to propagate far from the Sun.

w - Shocks while propagating in the solar wind, e.g., approaching the detector. Such acceleration is indicated by energetic storm particles (see Figure 1). (The distinction between *c* and *w* sites will be discussed further.)

We then classify SEP populations with a two-letter code indicating the observationally indicated sites of origin and final acceleration, respectively. After particles are initially accelerated at one site, that could be their final site of acceleration, or there could be further acceleration farther out as a shock propagates toward the observer. Thus we consider valid classifications to include *ff*, *fc*, *fw*, *cc*, *cw*, and *ww*. If an analysis of observed data were to indicate an invalid combination such as *wc* (which we consider invalid because final acceleration should take place after initial acceleration, and CME-driven shocks do not move from the solar wind back into the corona), such an observation should be interpreted as falsifying the methodology we use to assign sites of origin (initial acceleration) and/or final acceleration (see further discussion in §4.2).

Among the valid combinations, the standard expectation for an impulsive event is *ff*, i.e., that there is no coronal mass ejection or shock, and all particle acceleration is at the flare site. For gradual events, there is evidence in the literature that SEP populations can have a *cc*, *cw*, or *ww* acceleration history (e.g., Lee and Ryan, 1986; Tan et al., 1989; and Gosling et al., 1981, respectively). This classification scheme also allows for the possibility of *fc* or *fw* populations, which would involve both "impulsive" and "gradual" acceleration mechanisms. However, in the present work we do not find evidence for such a "mixed" acceleration history, nor are we aware of evidence in the literature for mixed bulk SEP populations. There is evidence that minority components may originate in different sites from bulk components, i.e., that moderate enhancements of ^{3}He/^{4}He and $\langle Q \rangle_{Fe}$ in certain gradual events are due to "contamination" from preceding impulsive events (Mason et al., 1999b, Popecki et al., 2001). This is one reason why the present work only considers the bulk SEP of a given element in their classification.

3. HOW TIME-INTENSITY DATA INDICATE THE SITE OF FINAL ACCELERATION

3.1 Qualitative Analysis

In most cases, a qualitative examination of time-intensity profiles can clearly identify prompt and delayed SEP components (Figure 1). A typical pattern is that impulsive events have only prompt components, while gradual events show delayed components at low energy (below $\sim$ 5 MeV/nucleon) and prompt components at higher energy, i.e., the prompt component has a much harder spectrum. The relative intensity of prompt and delayed components also depends on the solar longitude of the event and magnetic connection with the observer (Cane et al., 1988). A prompt component indicates an *f* or *c* final acceleration site, while a delayed component indicates a *w* final acceleration site.

It is worthwhile to comment on the distinction between *c* and *w* sites. Because of observational distinctions, particles with *c* and *w* final acceleration sites (i.e., prompt and delayed components from gradual events) were originally given completely different names: solar energetic particles (SEP; also called solar cosmic rays in the past) and energetic storm particles (ESP), respectively. Nowadays both are included in the term SEP based on the understanding that both kinds of components from gradual events are apparently accelerated by CME-driven shocks, either while they are close to the Sun (*c*) or out in the solar wind (*w*; see Figure 2). Now the pendulum is swinging to the other extreme: some researchers declare on theoretical grounds that a distinction cannot be made between these components, or that it should not be considered a dichotomy. Therefore, we take this opportunity to remind the reader of the various observed differences.

A prompt component exhibits a rapid, dispersive onset and peak, followed by a steady decay in intensity vs. time. Thus such SEP populations indicate a relatively short-duration injection of particles, followed by transport in the interplanetary medium, where pitch angle scattering due to magnetic irregularities leads to the late-time decay in intensity. A prompt peak arrives sufficiently quickly that a CME-driven shock from that event could not have traveled far from the Sun before releasing particles into the interplanetary medium, therefore representing a near-solar (*f* or *c*) final acceleration site. On the other hand, a delayed component is generally found to exhibit a non-dispersive peak at approximately the time when an interplanetary shock passes the detector, some days after the occurrence of the solar event. This indicates a *w* final acceleration site, at the interplanetary shock while propagating through the solar wind. Another observational difference is that the two components generally have very different spectra, as mentioned above. Finally, we note that the solar wind composition is known to vary strongly with position, and that *c* and *w* sites have very different plasma densities, so we might well expect charge state (see §4) or other abundance differences. Therefore, we want our classification of SEP populations to distinguish between *c* and *w* acceleration sites and to permit a compositional comparison between *c*- and *w*-accelerated material, according to the theme of this Issue.

Sometimes both prompt and delayed components are present for a single energy range, and in that case they can usually be visually distinguished. Data sets in a narrow energy band where prompt and delayed components merge into an undistinguished continuum are somewhat unusual and specific to a certain energy range.

In this work, we only perform a qualitative analysis of SEP data, which according to the above does not distinguish between *f* and *c* final acceleration sites, both of which are manifest as near-solar injections. Therefore, assuming a valid time sequence (see §2) and drawing from the consensus in the community that when a shock is present it dominates the particle acceleration, if there is evidence for a *c* or *w* origin or the presence of a CME or associated shock, we assign a *c* final acceleration site, and otherwise we assign an *f* final acceleration site. This approach would permit a classification of *fc* or *fw* (i.e., a mixed impulsive/gradual acceleration history) if such an SEP population were observed.

3.2 Quantitative Analysis

The previous point raises an interesting question - can the duration of a near-solar injection distinguish between *f* and *c* final acceleration sites, perhaps by a quantitative analysis? Reames and Stone (1986) claimed that impulsive (i.e., *ff*) populations have a faster duration of injection, based on the time-intensity plots of 1 gradual event and 4 impulsive events in adjacent time periods, and neglecting interplanetary transport. The detailed deconvolution of interplanetary transport effects by Ruffolo et al. (1998) yielded similar results for 1 gradual event and 1 impulsive event. This question definitely needs to be examined for a larger sample of events.

The quantitative deconvolution of interplanetary transport effects for a near-solar injection (prompt component) is possible because of modern improvements in the numerical simulation of such processes, including pitch angle scattering and focusing, as well as solar wind effects such as convection and adiabatic deceleration. Consistent simulation results for SEP transport have been obtained by Ruffolo (1995), Hatzky et al. (1997), Lario et al. (1998), and Kocharov et al. (1998). Such simulations can be employed to determine the near-solar injection profile that best fits the observed SEP intensity vs. time or intensity and anisotropy vs. time (Ruffolo et al., 1998). Analogous fits for *w* acceleration are more difficult; no research to date has married accurate simulations of the shock evolution, particle injection and acceleration, and interplanetary transport.

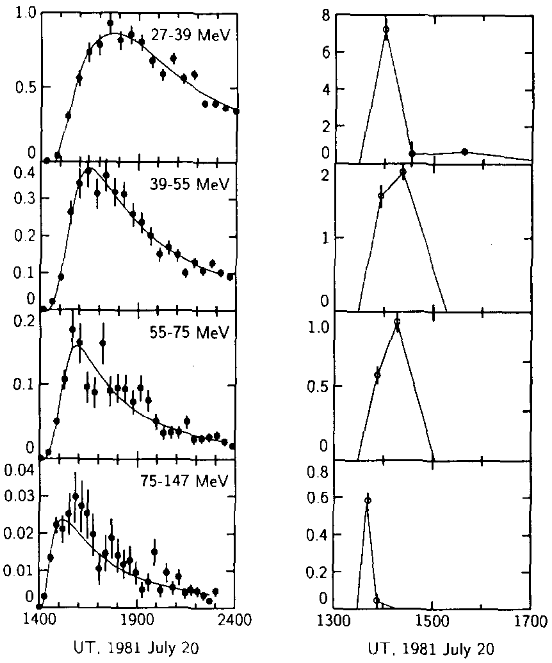

Fig. 3. Fits to the (a) observed proton intensity vs. time on July 20, 1981 in four energy bins for (b) optimized piecewise linear injection profiles. Note the expanded time scale in the right panels (after Ruffolo et al., 1998).

Figure 3 shows results for *c* final acceleration of protons during the gradual event of July 20, 1981. [Note that the bottom axis numbering of the right panel was incorrect in the original publication (while correct numerical values were listed in a table); that has been corrected here.] The results of such an analysis are the injection profile as a function of time and energy, the injected spectrum as a function of energy, and the mean free path of interplanetary scattering as a function of energy. For the case shown in Figure 3, we see that there is a much shorter duration of injection for the highest energy protons (verified by two independent fitting techniques), indicating that the CME-driven shock lost the ability to accelerate protons to $\sim$ 100 MeV after traveling a certain distance from the Sun. This is consistent with the trend that farther out, in the solar wind, the shock produces a much softer spectrum. These results demonstrate that such quantitative fitting can provide further insight into the *f* and *c* acceleration processes.

4. HOW IONIC CHARGE STATES INDICATE THE SITE OF ORIGIN

4.1 Observations and Physical Implications

Low-energy (sub-MeV/nucleon) ionic charge states can serve as good diagnostics of their source plasma because such ions are not stripped during their passage through the low-density interplanetary medium. As an example, the time scale for collisional ionization of energetic Fe^{+10} at Earth orbit is at least $\sim$50 years. Iron, silicon, and magnesium are the abundant SEP species for which there is a wide range of observed charge states, so these elements serve as particularly good diagnostics.

Figure 4 shows a histogram of mean Fe charges observed by the Solar Energetic Particle Ionic Charge Analyzer on board the Advanced Composition Explorer spacecraft (ACE/SEPICA) for 18 SEP events during 1998 (Möbius et al., 2000; a listing of the data was kindly provided by the authors). Our interpretation is that these mean charges are roughly separated into three groups, which can be identified with *w*, *c*, and *f* sites of origin (to be justified shortly). [On a cautionary note, this is a matter of interpretation, and the event statistics presented in the literature so far are still too limited for a final conclusion.] Similar groups can be identified for Si and Mg mean charges, and almost every event falls in the same group for all three elements. The mean charge observations for Ne and O are also useful, but with current experimental uncertainties one can only identify 2 groups, i.e., *w* and *c* origins are not distinguished. As a caveat, some of these SEP events occurred closely together in time and also had similar mean charges; therefore, it is likely that not all 18 events are physically independent of each other. Note that a similar identification of sub-MeV/nucleon SEP of low and medium mean charges with *w* and *c* sites of origin, respectively, has been independently suggested by Bogdanov et al. (2000).

At low energies, the physical basis for identification of the origin is rather clear:

- $w \rightarrow$ low $\langle Q \rangle$: In the interplanetary medium, there is negligible stripping, and at most a selection effect on the mean charge. Such a selection effect can give $\Delta\langle Q \rangle \sim 1$ to 2 at 0.5 MeV/nucleon (Bogdanov et al., 2000, Klecker et al., 2001).

- $f \leftrightarrow$ high $\langle Q \rangle$: even under extreme, equilibrium conditions, Fe, Si, and Mg ions of high $\langle Q \rangle$ have not been stripped by more than one charge unit for $E < 0.6$ MeV/nucleon (Ostryakov et al., 2000; Kartavykh et al., 2001).

- $c \leftarrow$ medium $\langle Q \rangle$ (by elimination; neither *f* nor *w* origins can explain such charges).

As a working hypothesis, these will be assumed to be 2-way implications (supporting evidence is presented in §4.2).

In this work, we use low-energy charge states as indicators of the site of origin, but other indicators could be used. A ^{3}He/^{4}He ratio greater than $\sim$ 0.1 has frequently been used to indicate an impulsive event, i.e., an *f* origin. Deficiencies of this ratio as an indicator are that it does not seem to distinguish between a *c* or *w* origin, and that as a minority species ^{3}He can be contaminated by material from preceding ^{3}He-rich events (Mason et al., 1999b). An advantage over low-energy ionic charge states is that this ratio can indicate an *f* origin in any energy range. Heavy element abundances might also be considered as indicators (see §1). These abundances are important but complicated and poorly understood, so we would rather consider these as "dependent variables," to be studied as a function of the "independent variables" of acceleration history, as indicated by diagnostics solidly grounded in basic physics.

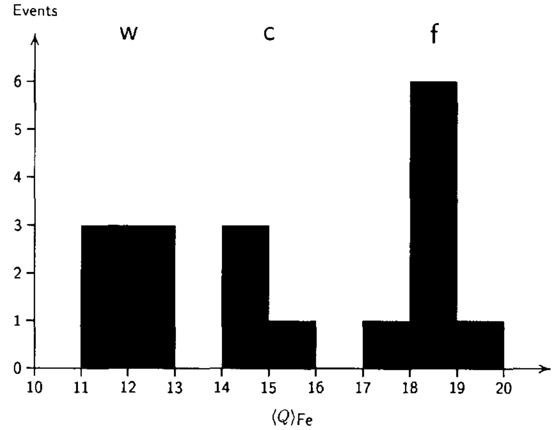

Fig. 4. Histogram of mean Fe charges in the energy range 0.18-0.44 MeV/nucleon for SEP events in 1998, as reported by Möbius et al. (2000).

4.2 Interpretation of Energy Dependence

The interpretation of ionic charge states at higher energy (above ~1 MeV/nucleon) is related to that at low energy. Since their discovery in 1997, energy-dependent charge states have been found to be fairly ubiquitous among SEP (Oetliker et al., 1997; Möbius et al., 1999b; Mazur et al., 1999; Bogdanov et al., 2000).

At higher energy, there is a likelihood of stripping in hot flare plasma and a possibility in the corona. Stripping does not occur in the solar wind, but there could be major selection effects with increasing energy (Klecker et al., 2001). Therefore, there is no compelling indication of the site of origin as there is at low energies, except in the sense that one would not expect lower charge states than those at low energy for a given origin.

Various explanations have been proffered for the energy dependence of mean charges. An admixture between material of *w* origin and *c* origin was suggested by Oetliker et al. (1997). Stripping in ambient (coronal) plasma has been considered, either in the limit of equilibrium charges (Reames et al., 1999) or for simultaneous calculations of acceleration and charge-changing reactions (Ostryakov and Stovpyuk, 1999; Barghouty and Mewaldt, 2000; Stovpyuk and Ostryakov, 2001). Selection effects have recently been considered by Klecker et al. (2001), in which certain ionic charge states are preferentially accelerated to higher energies. A combination of selection and admixture effects has been proposed by Tylka et al. (2001).

This issue is relevant to our classification strategy as follows: We propose to identify the site of origin from low-energy mean charges as indicated in Figure 4. Of the proposed explanations of the energy dependence of charge states at $E > 0.5$ MeV/nucleon, the admixture and selection ideas attribute low charge states (e.g., $\langle Q \rangle_{\mathrm{Fe}} \approx 11$) of low-energy SEP ($\sim$0.5 MeV/nucleon) to a wind origin, while the stripping idea assumes a coronal origin at all energies in order to provide sufficient material for stripping.

Here we identify some arguments in favor of admixture or selection mechanisms, and the identification of low charge states of sub-MeV/nucleon SEP with a *w* origin in Bogdanov et al. (2000) and the present work. If such SEP are of *w* origin, the only valid acceleration history is *ww*, which is consistent with observations: so far low charge states have only been noted for *w* final acceleration sites. Also, we know that a there is a mixture between *c* and *w* final acceleration sites in the energy range under consideration, whereas we do not know that such a large amount of stripping takes place. It seems arbitrary to assign low, solar wind-like charge states to a coronal origin for the events of Oct./Nov., 1992 and Nov. 6, 1997, when there are other gradual events for which wind-like charge states can be shown to have a wind origin, e.g., when they track temporal changes in the solar wind charges during disturbed interplanetary conditions (Popecki et al., 2000). Similarly, assigning such charge states to the corona would require a dichotomy of source conditions in the corona: sometimes producing low (wind-like) values for $\langle Q \rangle$ and sometimes moderate values. Furthermore, there is a specific problem with the stripping model for Oct./Nov., 1992 in that only Fe exhibits a significant energy dependence, whereas model results for stripping during acceleration predict such a dependence for other elements also (Ruffolo, 1997; Barghouty and Mewaldt, 2000). Therefore, we consider the admixture and selection mechanisms to be more likely explanations of energy-dependent charge states.

On Nov. 6, 1997, an event that exhibited a strong energy dependence in ionic charge states, unusually low mean charges were observed at the low range of SEPICA energies. Perhaps this is consistent with selective acceleration of the higher charge states within the solar wind distribution, leaving a lower mean charge at low energies, or with a combination of selection and admixture effects (Tylka et al., 2001). With regard to the *w/c* admixture idea, it is interesting that with increasing energy, the measured mean charges on Nov. 6, 1997 increase in tandem with a transition from a delayed to a prompt time-intensity profile. Clearly more work is needed on this issue. As a final point, we note that if one were to find low, wind-like charge states at sub-MeV/nucleon energies during a prompt component, our interpretation of a *w* origin for low mean charges would be inconsistent with the near-solar (*f* or *c*) injection site and would thereby be falsified.

5. APPLICATION TO RECENT SOLAR EVENTS

Table 1 shows the results of applying the scheme proposed in this paper to classify low-energy SEP ion populations from some events in 1997 and 1998. As a reminder, the two-letter classification refers to sites of origin and final acceleration, respectively. We identify sites of origin from low-energy ionic charge states measured by ACE/SEPICA, and sites of final acceleration from a qualitative examination of publicly available Ultra Low Energy Isotope Spectrometer (ACE/ULEIS) time-intensity profiles. In each case, both kinds of data were available for Fe ions of 0.18-0.44 MeV/nucleon, and data that were available for other ions corroborated the classification.

Table 1. Sample Classifications of SEP Ion Populations

Year/Day of year	Date	Classification
1997/310	Nov 6	*ww*
1998/119	Apr 29	*ww*
1998/122	May 2	*cw*
1998/126	May 6	*cc*
1998/251	Sep 8	*ff*
1998/252	Sep 9	*ff*

Sources: Möbius et al., 1999b, Mason et al., 1999a; Möbius et al., 2000, ACE/ULEIS online data (http://www.srl.caltech.edu/ACE/ASC)

Of these selected SEP events, charge state data at higher energies are available only for Nov. 6, 1997. The interesting energy dependence of mean ionic charges and time-intensity profiles for this event was discussed in §4.2.

It is perhaps surprising that even for low-energy SEP ions, four types of acceleration histories can be identified: *ff*, *cc*, *cw*, and *ww*. The first is characteristic of impulsive events, and the latter three have been discussed in the literature for gradual events. However, *cc* and *cw* acceleration histories have been proposed for higher energies, while the standard picture of gradual events attributes low energy SEP ions to acceleration out of the solar wind by an interplanetary shock, or *ww* populations. Thus even this small sample of events demonstrates the variety of acceleration histories experienced by "gradual" SEP of a given energy range, and the danger in taking the standard picture too literally. Another interesting result is what is not found: mixed impulsive/gradual acceleration histories such as *fc* and *fw* have not been identified so far.

6. DISCUSSION AND CONCLUSIONS

The observed lack of "mixed" acceleration histories justifies the classification of solar events as impulsive or gradual. Indeed, we do not intend to criticize this existing classification of solar events, but rather to point out the problems currently experienced in its application (§1), and to propose that an additional classification of SEP *populations* is helpful for improving the understanding of recent, detailed SEP observations. We observe a variety of SEP acceleration histories for gradual solar events, so for theoretical or computational models to explain observed data, it is crucial to account for the variety of acceleration histories, or else to clarify that a given model only seeks to explain SEP of a certain acceleration history.

We should point out observations that do not readily fit into the proposed classification scheme: the unusual charge states during the CME of May 2-3, 1998 (Popecki et al., 2000). As the mean charge of SEP Fe rose to about 16 in tandem with the hot component of the peculiar hot + cold solar wind charge distribution (Gloeckler et al., 1999), this probably represented a hot source plasma that was not flare plasma in the standard sense; rather, high charge states are frequently found in the plasma within magnetic clouds (Henke et al., 2001). We therefore consider this SEP population an enigma, pending an understanding of the underlying solar wind charge states, rather than force-fitting it into categories designed for conventional SEP events.

While this paper has concentrated on SEP heavy ions, we have not forgotten about electrons or protons; these can be classified in a similar way if indicators of their origin can be found. For energetic SEP electrons, such indicators may be provided by spectra, which exhibit a sharp break for impulsive events (Moses et al., 1989), and a comparison with gamma-ray spectra from the flare site, indicating thin-target or thick-target emission (Dröge et al., 1990).

In conclusion, the goal of the proposed scheme is to classify an observed SEP population of a given species, energy range, and time period using robust indicators of its acceleration history. We express the acceleration history in terms of the site of origin and the site of final acceleration, each of which can be hot flare plasma (*f*), a shock propagating through the corona (*c*), or a shock propagating through the solar wind (*w*). The site of origin is indicated by low-energy ionic charge states, while the site of final acceleration is determined from the time-intensity profile. This scheme avoids problems that have been encountered in classifying the parent solar event as impulsive or gradual. We performed the SEP classification for a sample of events, based on publicly available ACE data, and found that each event exhibits impulsive or gradual acceleration histories; no mixed acceleration histories are seen. The impulsive acceleration history is classified as *ff*, while gradual events are found to produce three types of SEP populations, even at low energies, with *cc*, *cw*, and *ww* acceleration histories. This SEP classification scheme should provide a more precise basis for further investigation of their composition and spectra.

With regard to the theme of this Issue (Solar Composition), SEP studies to date have relied on a classification of the solar event, which has not always specified the actual site of origin (i.e., seed population) of a given SEP population. While impulsive (*ff*) events exhibit abundance anomalies that provide interesting clues to the acceleration process at the flare site, SEP from gradual events have the potential to tell us more about the source material. With this new scheme, investigators will be able to compare SEP of *w* origin with solar wind abundances, which are known to exhibit interesting variations, e.g., between slow and fast wind. It will also be possible to compare whether abundances are different for a *c* origin, providing remote sensing of coronal abundances. As a further example, one can check for an effect of the final acceleration site by comparing *cc* and *cw* populations. Therefore, in addition to assisting the study of acceleration processes, a key benefit of this classification scheme may be to turn solar energetic particles into a better tool for solar composition investigations.

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REFERENCES

Barghouty, A. F., and R. A. Mewaldt, Simulation of Charge-Equilibration and Acceleration of Solar Energetic Ions, in ACE 2000 Symposium (AIP Conf. Proc. 528), eds. R. A. Mewaldt et al., AIP, College Park, MD, 2000.

Bogdanov, A. T., B. Klecker, E. Möbius, M. Hilchenbach, L. M. Kistler, et al., Energy Dependence of Ion Charge States in CME Related Solar Energetic Particle Events Observed with ACE/SEPICA and SOHO/STOF, in ACE 2000 Symposium (AIP Conf. Proc. 528), eds. R. A. Mewaldt et al., AIP, College Park, MD, 2000.

Bryant, D. A., T. L. Cline, U. D. Desai, and F. B. McDonald, Explorer 12 Observations of Solar Cosmic Rays and Energetic Storm Particles after the Solar Flare of September 28, 1961, *J. Geophys. Res.*, **67**, 4983-5000, 1962.

Cane, H. V., R. E. McGuire, and T. T. von Rosenvinge, Two Classes of Solar Energetic Particle Events Associated with Impulsive and Long-Duration Soft X-Ray Flares, *Astrophys. J.*, **301**, 448-459, 1986.

Cane, H. V., D. V. Reames, and T. T. von Rosenvinge, The Role of Interplanetary Shocks in the Longitude Distribution of Solar Energetic Particles, *J. Geophys. Res.*, **93**, 9555-9567, 1988.

Cohen, C. M. S., A. C. Cummings, R. A. Leske, R. A. Mewaldt, E. C. Stone, et al., Inferred Charge States of High Energy Solar Particles from the Solar Isotope Spectrometer on ACE, *Geophys. Res. Lett.*, **26**, 149-152, 1999.

Dröge, W., D. J. Forrest, and B. Klecker, Solar Flare Electron and Gamma Ray Spectra, *21st Intl. Cosmic Ray Conf.*, **5**, 84-87, 1990.

Evenson, P., P. Meyer, S. Yanagita, and D. J. Forrest, Electron-Rich Particle Events and the Production of Gamma-Rays by Solar Flares, *Astrophys. J.*, **283**, 439-449, 1984.

Fisk, L. A., ^{3}He-Rich Flares: A Possible Explanation, *Astrophys. J.*, **224**, 1048-1055, 1978.

Forbush, S. E., Three Unusual Cosmic-Ray Increases Possibly Due to Charged Particles from the Sun, *Phys. Rev.*, **70**, 771-772, 1946.

Garrard, T. L., E. C. Stone, and R. E. Vogt, in High Energy Phenomena on the Sun Symposium Proceedings (NASA SP-342), eds. R. Ramaty and R. G. Stone, NASA, Washington, DC, p. 341, 1973.

Gloeckler, G., L. A. Fisk, S. Hefti, N. A. Schwadron, T. H. Zurbuchen, et al., Unusual Composition of the Solar Wind in the 2-3 May 1998 CME Observed with SWICS on ACE, *Geophys. Res. Lett.*, **26**, 157-160, 1999.

Gosling, J. T., J. R. Asbridge, S. J. Bame, W. C. Feldman, R. D. Zwickl, et al., Interplanetary Ions during an Energetic Storm Particle Event: The Distribution Function from Solar Wind Thermal Energies to 1.6 MeV, *J. Geophys. Res.*, **86**, 547-554, 1981.

Hatzky, R., M.-B. Kallenrode, and J. Schmidt, The Effect of Adiabatic Deceleration on Angular Distributions of Solar Energetic Particles, *25th Intl. Cosmic Ray Conf.*, **1**, 245-248, 1997.

Henke, T., J. Woch, R. Schwenn, U. Mall, G. Gloeckler, et al., Ionization State and Magnetic Topology of Coronal Mass Ejections, *J. Geophys. Res.*, **106**, 10597-10613, 2001.

Hsieh, K. C., and J. A. Simpson, The Relative Abundances and Energy Spectra of ^{3}He and ^{4}He from Solar Flares, *Astrophys. J.*, **162**, L191-L196, 1970.

Hurford, G. J., R. A. Mewaldt, E. C. Stone, and R. E. Vogt, Enrichment of Heavy Nuclei in ^{3}He-Rich Flares, *Astrophys. J.*, **201**, L95-L97, 1975.

Kartavykh, Yu. Yu., S. Wannawichian, D. Ruffolo, and V. M. Ostryakov, Charge State Distributions of Mg and Si from Stochastic Acceleration in Impulsive Solar Flares, *This issue*, 2001.

Klecker, B., A. T. Bogdanov, D. Hovestadt, R. F. Wimmer-Schweingruber, R. Schaerer, et al., Ionic Charge Distributions of Suprathermal Particles and Their Solar Wind Source in CME Related Events, *This issue*, 2001.

Klecker, B., D. Hovestadt, G. Gloeckler, F. M. Ipavich, M. Scholer, C. Y. Fan, and L. A. Fisk, Direct Determination of the Ionic Charge Distribution of Helium and Iron in ^{3}He-Rich Solar Energetic Particle Events, *Astrophys. J.*, **281**, 458-462, 1984.

Kocharov, L., R. Vainio, G. A. Kovaltsov, and J. Torsti, Adiabatic Deceleration of Solar Energetic Particles as Deduced from Monte Carlo Simulations of Interplanetary Transport, *Solar Phys.*, **182**, 195-215, 1998.

Lario, D., B. Sanahuja, and A. M. Heras, Energetic Particle Events: Efficiency of Interplanetary Shocks as 50 keV $< E <$ 100 MeV Proton Accelerators, *Astrophys. J.*, **509**, 415-434, 1998.

Lee, M. A., and J. M. Ryan, Time-Dependent Coronal Shock Acceleration of Energetic Solar Flare Particles, *Astrophys. J.*, **303**, 829-842, 1986.

Luhn, A., B. Klecker, D. Hovestadt, and E. Möbius, The Mean Ionic Charge of Silicon in ^{3}He-Rich Solar Flares, *Astrophys. J.*, **317**, 951-955, 1987.

Mason, G. M., C. M. S. Cohen, A. C. Cummings, J. R. Dwyer, R. E. Gold, et al., Particle Acceleration and Sources in the November 1997 Solar Energetic Particle Events, *Geophys. Res. Lett.*, **26**, 141-144, 1999a.

Mason, G. M., G. Gloeckler, and D. Hovestadt, Temporal Variations of Nucleonic Abundances in Solar Flare Energetic Particle Events. II - Evidence for Large-Scale Shock Acceleration, *Astrophys. J.*, **280**, 902-916, 1984.

Mason, G. M., J. E. Mazur, and J. R. Dwyer, ^{3}He Enhancements in Large Solar Energetic Particle Events, *Astrophys. J.*, **525**, L133-L136, 1999b.

Mazur, J. E., G. M. Mason, M. D. Looper, R. A. Leske, and R. A. Mewaldt, Charge States of Solar Energetic Particles

Using the Geomagnetic Cutoff Technique: SAMPEX Measurements in the 6 November 1997 Solar Particle Event, *Geophys. Res. Lett.*, **26**, 173-176, 1999.

Miller, J. A., and A. F. Viñas, Ion Acceleration and Abundance Enhancements by Electron Beam Instabilities in Impulsive Solar Flares, *Astrophys. J.*, **412**, 386-400, 1993.

Möbius, E., B. Klecker, M. A. Popecki, L. M. Kistler, A. B. Galvin, et al., Variation of Ionic Charge States between Solar Energetic Particle Events as Observed with ACE SEPICA, *26th Intl. Cosmic Ray Conf.*, **6**, 87-90, 1999a.

Möbius, E., B. Klecker, M. A. Popecki, D. Morris, G. M. Mason, et al., Survey of Ionic Charge States of Solar Energetic Particle Events During the First Year of ACE, ACE 2000 Symposium (AIP Conf. Proc. 528), eds. R. A. Mewaldt et al., AIP, College Park, MD, 2000.

Möbius, E., M. Popecki, B. Klecker, L. M. Kistler, A. Bogdanov, et al., Energy Dependence of the Ionic Charge State Distribution during the November 1997 Solar Energetic Particle Event, *Geophys. Res. Lett.*, **26**, 145-148, 1999b.

Moses, D., W. Dröge, P. Meyer, and P. Evenson, Characteristics of Energetic Solar Flare Electron Spectra, *Astrophys. J.*, **346**, 523-530, 1989.

Oetliker, M., B. Klecker, D. Hovestadt, G. M. Mason, J. A. Mazur, et al., The Ionic Charge of Solar Energetic Particles with Energies of 0.3-70 MeV per Nucleon, *Astrophys. J.*, **477**, 495-501, 1997.

Ostryakov, V. M., Yu. Yu. Kartavykh, D. Ruffolo, G. A. Kovaltsov, and L. Kocharov, Charge State Distributions of Iron in Impulsive Solar Flares: Importance of Stripping Effects, *J. Geophys. Res.*, **105**, 27315-27322, 2000.

Ostryakov, V. M., and M. F. Stovpyuk, Charge State Distributions of Iron in Gradual Solar Energetic Particle Events, *Solar Phys.*, **189**, 357-372, 1999.

Pallavicini, R., S. Serio, and G. S. Vaiana, A Survey of Soft X-ray Limb Flare Images - The Relation between Their Structure in the Corona and Other Physical Parameters, *Astrophys. J.*, **216**, 108-122, 1977.

Popecki, M. A., M. Desai, R. M. Skoug, C. W. Smith, E. Möbius, et al., SEP Fe Charge States in ^{3}He-Rich Interplanetary Shock Events, *27th Intl. Cosmic Ray Conf.*, **8**, 3153-3156, 2001.

Popecki, M. A., T. H. Zurbuchen, R. M. Skoug, C. W. Smith, A. B. Galvin, et al., Simultaneous High Fe Charge State Measurements by Solar Energetic Particle and Solar Wind Instruments, in ACE 2000 Symposium (AIP Conf. Proc. 528), eds. R. A. Mewaldt et al., AIP, College Park, MD, 2000.

Reames, D. V., Acceleration of Energetic Particles by Shock Waves from Large Solar Flares, *Astrophys. J.*, **358**, L63-L67, 1990.

Reames, D. V., C. K. Ng, and A. J. Tylka, Energy-Dependent Ionization States of Shock-Accelerated Particles in the Solar Corona, *Geophys. Res. Lett.*, **26**, 3585-3588, 1999.

Reames, D. V., and R. G. Stone, The Identification of Solar ^{3}He-Rich Events and the Study of Particle Acceleration at the Sun, *Astrophys. J.*, **308**, 902-911, 1986.

Ruffolo, D., Effect of Adiabatic Deceleration on the Focused Transport of Solar Cosmic Rays, *Astrophys. J.*, **442**, 861-874, 1995.

Ruffolo, D., Charge States of Solar Cosmic Rays and Constraints on Acceleration Times and Coronal Transport, *Astrophys. J.*, **481**, L119-L122, 1997.

Ruffolo, D., T. Khumlumlert, and W. Youngdee, Deconvolution of Interplanetary Transport of Solar Energetic Particles, *J. Geophys. Res.*, **103**, 20591-20602, 1998.

Stovpyuk, M. F., and V. M. Ostryakov, Heavy Ions from the 6 November 1997 SEP Event: A Charge-Consistent Acceleration Model, *Solar Phys.*, **198**, 163-167, 2001.

Tan, L. C., G. M. Mason, B. Klecker, and D. Hovestadt, Seed Population for about 1 MeV per Nucleon Heavy Ions Accelerated by Interplanetary Shocks, *Astrophys. J.*, **345**, 572-583, 1989.

Temerin, M., and I. Roth, The Production of ^{3}He and Heavy Ion Enrichments in ^{3}He-Rich Flares by Electromagnetic Hydrogen Cyclotron Waves, *Astrophys. J.*, **391**, L105-L108, 1992.

Tylka, A. J., Cohen, C. M. S., Dietrich, W. F., Maclennan, C. G., McGuire, R. E., et al., Evidence for Remnant Flare Suprathermals in the Source Population of Solar Energetic Particles in the 2000 Bastille Day Event, *Astrophys. J.*, **558**, L59-L63, 2001.

von Rosenvinge, T. T., C. M. S. Cohen, E. R. Christian, A. C. Cummings, R. A. Leske, et al., Time Variations of Solar Energetic Particle Abundances Observed by the ACE Spacecraft, *26th Intl. Cosmic Ray Conf.*, **6**, 131-134, 1999.