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SOLAR ENERGETIC Fe CHARGE STATE MEASUREMENTS: IMPLICATIONS FOR ACCELERATION BY CORONAL MASS EJECTION–DRIVEN SHOCKS

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ABSTRACT

A variety of studies have demonstrated that large (gradual) solar energetic particle (SEP) events are produced by shocks driven by fast coronal mass ejections (CMEs). As the CME-driven shocks propagate through the corona and interplanetary space, they accelerate energetic particles from ambient plasma. A key piece of evidence supporting the CME-driven shock acceleration scenario is the SEP Fe mean charge state measurements from $\sim$1 MeV nucleon^{-1} to 200–600 MeV nucleon^{-1}, which are consistent with each other and imply acceleration in either the high corona or interplanetary space. However, the SEP Fe mean ionic charge state measurements are generally inconsistent with typical quasi-stationary interstream or coronal hole solar wind Fe charge state measurements, despite the fact that gradual SEP time profiles indicate that shock acceleration subsequent to departure from the corona dominates the SEP observations. These Fe results indicate that neither overtaken solar wind nor charge state biasing of the solar wind as it is swept up and accelerated by the shock are the dominant component accelerated by the CME-driven shock. We suggest that the dominant component for both the plasma and SEP populations appears to be expelled "coronal" plasma stored in the so-called sheath region (between the CME and the shock front), and that swept-up solar wind generally makes only a minor contribution to the SEPs. The only concurrent observation of SEP and solar wind charge states made to date (by instruments on board *ISEE 3* in 1978 September) supports this view. We suggest that coordinated SEP and solar wind charge state observations should be given high priority by state-of-the-art instruments currently deployed on board the *Solar Anomalous Magnetospheric Particle Explorer*, *Wind*, and the *Solar and Heliospheric Observatory*.

Subject headings: acceleration of particles — solar wind — Sun: particle emission — shock waves

1. INTRODUCTION

During the past several years, measurements have provided compelling evidence (Reames 1990a, 1990b, 1992, 1993; Kahler 1992; Gosling 1993) for two classes of solar energetic particle (SEP) events, which are typically labeled "impulsive" (^{3}He-rich or solar flare accelerated) and "gradual" (coronal mass ejection [CME] driven shock accelerated). These two classes are readily distinguished by the mean charge states of Fe ions.[2] For low-energy ($\sim$1 MeV nucleon^{-1}) Fe ions (Luhn et al. 1985, 1987), the average for impulsive SEP events is $\langle Q \rangle = 20.5 \pm 1.2$, while the average for 12 gradual events is $\langle Q \rangle = 14.1 \pm 0.2$. The recent SEP Fe $\langle Q \rangle = 14.2 \pm 1.4$ result at 200–600 MeV nucleon^{-1} (Tylka et al. 1995a) for the large events of 1989 September–October, as well as more recent measurements from the *Solar Anomalous Magnetospheric Particle Explorer* (*SAMPEX*) at intermediate energies (Leske et al. 1995; Oetliker et al. 1995, 1996), demonstrates that CME-driven shock acceleration is the dominant mechanism from one to several hundred MeV nucleon^{-1} (Fig. 1, *right*).

The Fe $\langle Q \rangle$ results are consistent with studies of (1) low-energy gradual SEP time profiles (Reames 1994; Lee & Ryan 1986), which show that interplanetary (IP) shock acceleration continues for days, and (2) correlations (Kahler 1994) between high-energy SEP and CME time profiles (St. Cyr & Burkepile 1990), which show that the CME-driven shock acceleration continues to GeV energies. The canonical scenario that emerges from energetic proton time-intensity profiles and studies of shock region plasma is that the shock overtakes, sweeps up, and accelerates the preceding ambient solar wind (SW). In this Letter, we compare SEP Fe $\langle Q \rangle$ measurements with results from in-ecliptic SW Fe charge state data and from isothermal coronal calculations. These comparisons indicate that the typical quasi-stationary[3] interstream (IS) or coronal hole (CH) solar wind is a minor contributor to the seed plasma accelerated by the CME-driven shocks. Instead, we suggest that a distinct region of expelled "coronal" plasma that propagates with the CME-driven shock is the dominant seed plasma for typical SEP events. A preliminary version of this work has been reported elsewhere (Boberg, Tylka, & Adams 1995).

2. SUMMARY OF SEP Fe IONIC CHARGE STATE MEASUREMENTS

In Figure 1 (*right*), we compare the SEP Fe mean charge state measurements from $\sim$1 MeV nucleon^{-1} (Luhn et al. 1985, 1987; Mason et al. 1995) to 200–600 MeV nucleon^{-1} (Tylka et al. 1995a). These mean Fe charge states are consistent with models of a $T \sim 2$ MK, isothermal corona (Arnaud & Raymond 1992). Recent $\sim$1 MeV nucleon^{-1} measurements (Mason et al. 1995) in two events are lower than earlier results (Luhn et al. 1985, 1987); nevertheless, the bulk of the measurements spanning three decades in energy made with three

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[2] Composite events, in which both acceleration mechanisms operate, have also been observed (Mason et al. 1989; Debrunner, Lockwood, & Ryan 1993).

[3] We use "quasi-stationary" to identify periods that are not "transient" flows, e.g., CMEs or shocks. We use "coronal hole" to mean the streams that are generally high speed and thought to be produced by outflow from the coronal hole regions observed on the Sun. We use "interstream" to mean the slow ($\langle v \rangle \approx 400$–450 km s^{-1}) solar wind flow observed in regions between the high-speed coronal hole flows.

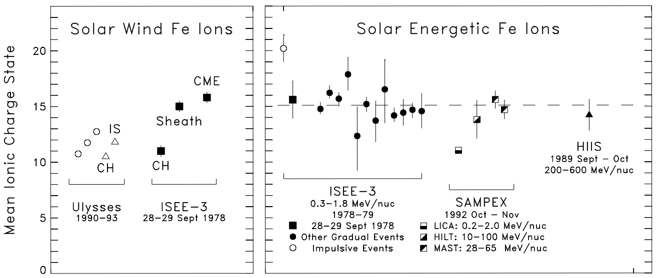

FIG. 1.—Summary of SW and SEP Fe $\langle Q \rangle$ measurements. *Left*: The SW measurements are (1) long-term averages from the Solar Wind Ion Composition Spectrometer on board *Ulysses* (*circles*: for three temperature regions inferred from oxygen ionization states [Ipavich et al. 1992]; *triangles*: for ambient interstream [Von Steiger & Geiss 1994] and out of the ecliptic coronal hole [Geiss et al. 1995] SW averages), and (2) from *ISEE 3* observations during 1978 September 28–29 (*filled squares*) for the overtaken CH flow, sheath, and CME-driver intervals (Ipavich et al. 1986; Galvin et al. 1987). *Right*: The SEP measurements are (1) 1978 September 28–29 (*filled square*) *ISEE 3* result (Hovestadt et al. 1982) concurrent with the SW results (*left*), (2) *ISEE 3* results for 12 large SEP events (Luhn et al. 1987), (3) *SAMPEX* (Leske et al. 1995; Mason et al. 1995; Oetliker et al. 1996), and (4) HIIS (Tylka et al. 1995a). Dashed line shows a weighted average $\langle\langle Q\rangle\rangle = 15.1$ over all gradual-event measurements except LICA (Mason et al. 1995). See the text for details. For completeness, also shown (*open circle*) is the reported $\langle Q \rangle$ for impulsive (i.e., flare-accelerated) solar energetic Fe ions (which are not relevant to this Letter).

different techniques give a consistent view of the mean SEP Fe charge state, i.e., implying acceleration occurs in low-density media.[4]

3. SUMMARY OF SOLAR WIND Fe CHARGE STATE MEASUREMENTS

Long-term averages of solar wind Fe ions (Fig. 1, *left*) have $\langle Q \rangle \approx 10.5$–13 (Ipavich et al. 1992; Von Steiger & Geiss 1994), depending on the solar area producing the SW flow. For example, coronal hole flows typically have Fe $\langle Q \rangle \sim 10.5$–11, while typical interstream solar wind flows have Fe $\langle Q \rangle \sim 11.5$–12. Fe $\langle Q \rangle$ in interstream flows shows significant variability, as illustrated in Figure 1 (*left*) by the data points from Ipavich et al. (1992). However, the vast majority of the SEP Fe $\langle Q \rangle$ (Fig. 1, *right*) are higher than all of these long-term SW averages, including the highest SW data point, which corresponds to the quintile of the interstream SW data in which the oxygen ionization temperatures are highest (>2 MK). Unless significant biasing of the Fe $\langle Q \rangle$ occurs during the acceleration process, the source plasma of SEP Fe apparently arises from a relatively rare regime in the solar wind.

In the vicinity of a fast (supersonic relative to the preceding SW plasma) CME-driven shock, the SW is divided into three regions: (1) the ambient, preexisting solar wind (preceding the shock/CME disturbance); (2) the CME plasma; and (3) the sheath region, located between the shock front and the CME. The sheath region consists of plasma with (1) elevated kinetic temperature and (2) enhanced density, flow speed, magnetic field strength, and field and plasma turbulence (Pudovkin 1977; Burlaga et al. 1981; Borrini et al. 1982; Tsurutani et al. 1984; Galvin et al. 1987; Gosling 1993). Ionic charge state measurements provide an important signature for distinguishing these regions (at least in the ecliptic), as the ionic charge states "freeze in" to their IP values by a few $R_\odot$ (Ipavich et al. 1992; Hundhausen, Gilbert, & Bame 1968; Bame et al. 1974; Owocki, Holzer, & Hundhausen 1983).

To our knowledge, the only SW Fe charge state measurements through the preceding ambient (coronal hole for this event) SW, sheath, and CME-driver regions (Ipavich et al. 1986; Galvin et al. 1987) were performed on 1978 September 28–29. Since we have observations from only this one event, it is not known how the sheath region Fe $\langle Q \rangle$ may vary from event to event. Moreover, since the 1978 September sheath observations cover only the last 3 hr of the sheath's 6 hr duration, it is also not known how the Fe $\langle Q \rangle$ may evolve within the sheath. For all three regions, we deconvolved the Fe $\langle Q \rangle$ (and error estimate) from the quoted Fe temperatures using the same model originally employed (Jordan 1969) to derive the temperatures. The inferred SW Fe $\langle Q \rangle$ averages for the preshock, sheath, and CME periods are shown in Figure 1 (*left*).

4. CONCURRENT SEP AND SOLAR WIND Fe MEASUREMENT

The 1978 September 28–29 event is also the only event to date in which we have concurrent solar wind and energetic particle charge state measurements. At ~1 MeV nucleon^{-1}, Hovestadt et al. (1982) report that Fe $\langle Q \rangle = 15.6 \pm 1.7$ (Fig. 1, *right*) for this event. This $\langle Q \rangle$ is 2.5 σ higher than the coronal hole SW value (Galvin et al. 1987) preceding the shock front, but it is consistent with both the sheath and CME-driver Fe plasma results (Fig. 1, *left*). A variety of CME plasma signatures[5] (Gosling 1993 and references therein) indicate that the CME plasma is magnetically isolated from the surrounding SW. In this scenario, the CME is not expected to make a significant contribution to the SEP source plasma. Thus, the concurrent SW and SEP Fe $\langle Q \rangle$ measurements, combined with the presumed magnetic isolation of the CME-driver plasma, strongly suggest that the sheath region plasma is the dominant Fe seed population for this SEP event.

It may be tempting to suggest that the elevated sheath region and SEP Fe $\langle Q \rangle$ results are produced by a significant charge state biasing of the preceding ambient solar wind Fe as it is swept up by the IP shock. However, Galvin et al. (1987) have argued against such a mechanism for producing the sheath region Fe observations during this event, since the observed Fe/H abundance ratio is roughly constant throughout the preshock CH and sheath observations. Given (1) the assumption that the SEP and sheath region Fe observations during this event are related and not merely an accidental coincidence and (2) the relatively large errors on the measurements, invoking rigidity or charge state dependent acceleration is neither required nor eliminated by these observations.

5. COMPARISON OF HIGH-ENERGY SEP Fe DATA WITH CHARGE STATE DISTRIBUTIONS

The recent Heavy Ions in Space (HIIS) data also provide a hint as to what the distribution of SEP Fe charge states may be. Tylka et al. (1995a) showed that the 150–600 MeV nucleon^{-1} SEP Fe measurements are inconsistent with any of the long-term average SW Fe charge state distributions

[4] Preliminary estimates (Leske et al. 1995) using the high-energy Fe results have put an upper limit of 600 μg cm^{-2} for initially neutral Fe passing through neutral H, which suggests that the high-energy Fe spends less than 1 s in the low corona ($\rho \approx 10^{10}$ atoms cm^{-3}) (Reames 1996). More realistic modeling would presumably produce a more stringent upper limit, since (1) the SEP Fe, SEP Fe seed plasma, and coronal plasma are ionized and (2) electron stripping dominates electron pickup for the relevant SEP energies.

[5] These signatures include distinct magnetic field features (strength, variance, and field rotations), counterstreaming electrons and protons, kinetic temperature decreases, low plasma β, high ionic charge states (at least in the ecliptic), density decreases, SEP flux decreases, etc.

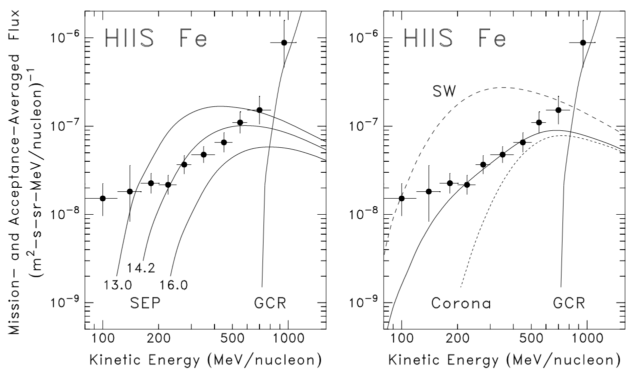

FIG. 2.—HIIS SEP Fe fluxes. *Left*: Solid curves show the expected SEP flux inside the magnetosphere (Tylka et al. 1995a) (with fluences outside the magnetosphere determined by the Chicago/*IMP-8*), assuming various $\langle Q \rangle$ values for SEPs in interplanetary space. Since the SEP Fe charge state distribution is unknown, the solid curves show charge state results assuming nearly flat distributions, with rms widths of ~2.5. Also shown is the expected GCR contribution to the HIIS flux. (*Right*) *Long dashes*: Expected flux at HIIS (Boberg et al. 1995) if SEPs had a typical in-ecliptic solar wind charge state distribution (Von Steiger & Geiss 1994) with $\langle Q \rangle = 11.8$. *Short dashes*: Expected flux if SEPs had a pure coronal charge state distribution (Arnaud & Raymond 1992) with $\langle Q \rangle = 14.5$. Solid curve is a linear combination of the coronal (90%) and typical solar wind (10%) distributions, yielding $\langle Q \rangle = 14.2$ for the SEPs. A better agreement with the lowest energy data point (which may have non-SEP contamination; Tylka et al. 1995b) can be obtained by adding 0.1 $Q = 6$ (Geiss et al. 1994) to the solar wind (hence, 0.1% to the SEPs).

(Ipavich et al. 1992; Von Steiger & Geiss 1994). Since the high-energy SEP Fe data are sensitive to assumptions about both $\langle Q \rangle$ and the shape of the charge state distribution, we compared this SEP Fe data to an energy- and time-independent linear combination (Fig. 2, *right*) of 10% long-term average interstream SW ($\langle Q \rangle = 11.8$) distribution (Von Steiger & Geiss 1994; triangle in Fig. 1, *left*) and 90% "coronal" ($\langle Q \rangle = 14.5$) (Arnaud & Raymond 1992), which reproduces the best-fit $\langle Q \rangle = 14.2$ (Tylka et al. 1995a). For reference, we also show the following: (1) the best-fit spectra (Fig. 2, *left*) using a flat charge state distribution (Tylka et al. 1995a), as well as the sensitivity of the spectra to the assumed $\langle Q \rangle$ for distributions with shapes and widths similar to the best-fit spectra; and (2) the expected spectra (Fig. 2, *right*) assuming either a pure (100%) SW or a pure "coronal" distribution. The "coronal" plus SW combination yields the best description of the 150–600 MeV nucleon^{-1} spectrum, suggesting a "coronal" plus SW seed population.

6. DISCUSSION

The SEP and SW Fe data indicate that the preceding ambient solar wind is not the dominant source of the sheath region and SEPs. Since the only sheath region Fe $\langle Q \rangle$ observation (Fig. 1, *left*) seems to be distinct from the preceding SW and significantly higher than typical quasi-stationary SW observations (Ipavich et al. 1992; Von Steiger & Geiss 1994), we suggest that the sheath region plasma is stored in the vicinity of the CME-driven IP shock front for some interval and is continually being accelerated by the shock (Lee 1983; Lee & Ryan 1986; Reames 1994). Our proposed acceleration of sheath plasma is consistent with a correlative study of plasma and SEP proton fluxes (Gosling et al. 1981; Gosling 1993) in the sheath region during the 1978 August 27 SEP event, which indicated a continuous spectrum from sheath plasma to SEP energies, identifying the sheath plasma as a source of energetic protons.

The initiation and duration of sheath-region plasma storage is not understood. A storage timescale significantly shorter than the timescale of the SEP event would be inconsistent with the distinct SEP and typical SW Fe $\langle Q \rangle$ measurements (Figs. 1 and 2). Because the timescale for SEP events decreases with increasing energy, the most stringent timescale limit generally is obtained from the low-energy SEP durations, which are known to continue to 1 AU. Therefore, the sheath region storage presumably endures for at least a substantial fraction of the CME-driven shock's transit time to 1 AU.

The most likely scenario is that the storage begins when the CME-driven shock is well established. The best indication of when the CME-driven shock is established was obtained (Kahler 1994) from correlations of CME coronagraph images with high-energy SEP time profiles that show that the SEP fluxes rise rapidly when the CME heights are beyond a few $R_\odot$. These correlations indicate that the CME-driven shock can be established in the high corona, at least in large events with CME speeds (~900 km s^{-1}) sufficient to establish coronal shocks (Steinolfson 1992). Since the CME-driver plasma tends to have higher Fe ionization states than the typical solar wind (Ipavich et al. 1986; Gosling 1993), the plasma stored in the sheath region during shock initiation could presumably have elevated Fe ionization states as well. We note that if the sheath region SW Fe charge state study (Galvin et al. 1987) reflects typical events, then the storage would typically continue until the IP shock reaches 1 AU.

While we have argued that the sheath region plasma is the dominant contributor to the SEP event, we do not preclude shock acceleration of the preceding ambient solar wind. Indeed, the fits (Fig. 2, *right*) of the 150–600 MeV nucleon^{-1} Fe spectrum suggest that the preceding ambient SW contributed ~10% of the high-energy Fe fluence in these 1989 September–October observations. While many factors contributing to the IP shock acceleration dynamics could affect the relative contributions of the stored sheath region and preceding ambient SW plasmas to SEP events, it seems likely that the contributions are related to the relative plasma densities in the two regions. At 1 AU, the average sheath region and local SW proton densities are about 26 cm^{-3} and 6.5 cm^{-3}, respectively (80%–20%), as determined from an average of 103 shock events (Borrini et al. 1982). If we assume that these relative densities are similar throughout the propagation between the Sun and 1 AU, then the average SEP Fe $\langle Q \rangle$ measurements suggest that the relative sheath region and preceding ambient solar wind plasma densities are determining factors in the shock acceleration process. These relative densities provide a plausible quantitative explanation for the sheath region's dominance of typical "gradual" events. Occasional observations (Fig. 1, *right*), particularly at low energies (e.g., Mason et al. 1995), may indicate the existence of events having a significantly larger contribution from the preceding ambient SW. The *ISEE 3* results at similar energies (Fig. 1, *right*) suggest that these events are infrequent. An enhanced contribution from the preceding ambient SW could be due to a combination of a relatively short sheath region storage interval, a smaller sheath to preceding SW relative density, and/or a substantial energy dependence of the acceleration timescale. Future SEP, SW, and coordinated Fe $\langle Q \rangle$ and charge state distribution measurements with the *SAMPEX*, *Solar and Heliospheric Observatory*, *Wind*, and the *Advanced Composition Explorer* will greatly improve our understanding of the ideas presented in this Letter.

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