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Solar energetic particle time-to-maximum studies with Wind and ACE

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Abstract. We examine the energy- and species-dependence of the so-called time-to-maximum (TTM), the elapsed time between the start of a solar energetic particle event and the occurence of the maximum particle intensity, using heavy-ion data from *Wind* and *ACE* and protons from *GOES*, *IMP8*, and the Climax Neutron Monitor. We have find a surprisingly simple ordering to the TTM data in the 1997 November 6 event. In other events, however, the data appear to be unamenable to simple ordering schemes.

1 Introduction

Solar energetic particle (SEP) time-to-maximum (TTM) studies (O'Gallagher *et al.* 1976) have fallen out of favor, perhaps because of their connection with discredited notions involving delta-function-like injections at the Sun followed by diffusive transport throught the corona. A large and diverse body of evidence now supports a central role for shocks driven by fast coronal mass ejections (CMEs) in producing SEP events. We now recognize that diffusion operates primarily along interplanetary magnetic flux tubes, and the notion of a point source has been replaced by an inhomogeneous, spatially-extended source (the shock front) that moves through space and evolves in time. In this context, the interpretation of TTM results is inherently more complex, reflecting not only particle transport, but also the changing potency of the CME-driven shock as it moves away from the Sun (Zank *et al.* 2000).

In addition, proton-generated Alfvén waves (Lee 1983, Ng *et al.* 1999; Reames 2000) play an important role in large SEP events. In these events, the interplanetary medium cannot be thought of as merely a static stage upon which the SEPs are released. Instead, the SEPs themselves roil the interplanetary medium, producing scattering mean free paths that vary with position and time and have a complex rigidity dependence (Reames et al. 2001; Tylka 2001). Since SEPs diffuse through all of this structure, it would seem unlikely that TTMs in large events will conform to any simple ordering according to particle speed (β), rigidity (R), or even some variable that combines the two.

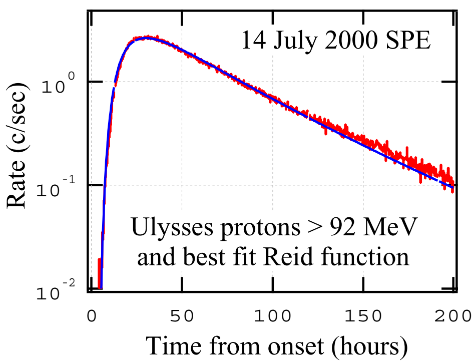

Fig. 1. Reid function fit to >92 MeV protons observed by *Ulysses* in the 2000 July 14 SPE. Data are 15-minute averages. *Ulysses* was at 3.2 AU and S62^o at the time.

Dietrich & Lopate (1999) revived TTM studies using data from the U. Chicago *IMP8* instrument. They examined several large events from 1989 and November 1997. They reported that TTM of Z$\geq$2 ions more or less organized themselves as power-laws in rigidity, provided that the Fe ions were less fully-ionized than lighter species. However, these conclusion were based on just a few, relatively wide energy bins, and there were large error bars on the TTMs due to limited ion statistics. Dietrich & Lopate (1999) also noted that proton TTMs were systematically lower than those of the heavy ions at the same rigidity.

In this paper, we examine TTMs using heavy-ion data from *Wind*/LEMT (von Rosenvinge *et al.* 1995) at ~3-20 MeV/nuc and from *ACE*/SIS (Stone *et al.* 1998) at ~7-150 MeV/nuc. These instruments provide high statistical precision as well as dense sampling of the energy spectrum for many elements.

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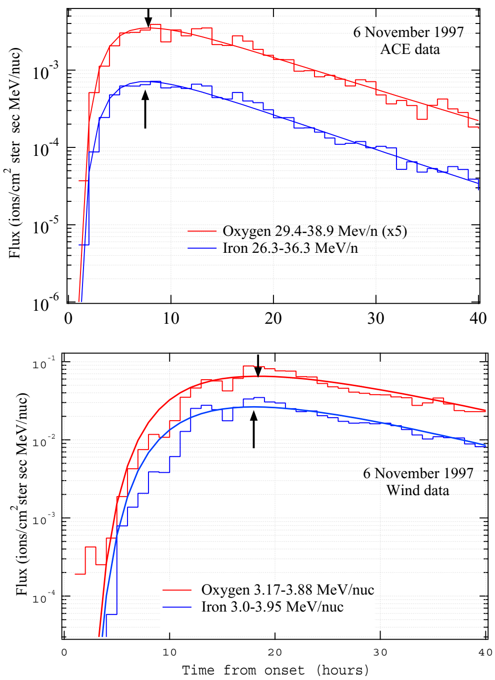

Fig. 2. Sample *ACE* (top) and *Wind* (bottom) iron and oxygen time-intensity profiles in the 1997 November 6 SPE. Data are hourly-averages. Time t=0 corresponds to 1200 UT. Curves are fits to eqn (1). Arrows mark the TOM from eqn (2).

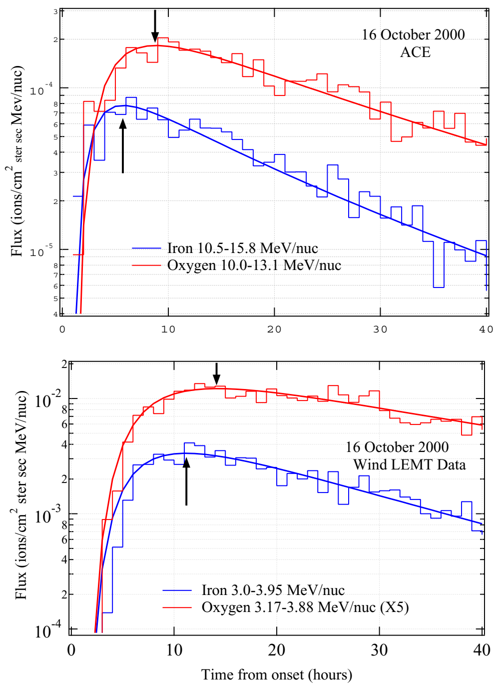

Fig. 3. Like Fig. 2, for the 2000 October 16 SPE.

We also use proton data at ∼5-500 MeV from *GOES* and the Chicago and NASA/Goddard instruments on *IMP8* and at ∼3 GeV from the Climax Neutron Monitor.

2 Time Intensity Profiles and TTM Determinations

For each species and energy bin, we first fit the observed time-intensity profile, using the functional form suggested by Reid (1964):

$$F(t) = \frac{K_0}{t} exp\left(\frac{-K_1}{t}\right) exp\left(\frac{-t}{K_2}\right) \quad (1)$$

We emphasize that we use this functional form simply because it is a flexible, empirical ansatz that gives excellent fits to many observed time profiles. We do not give any credence to the model which originally motivated it. As an example of how well eqn (1) can do, Fig. 1 shows >92 MeV protons observed by *Ulysses* in the 2000 July 14 solar particle event (SPE). This *Ulysses* profile is somewhat smoother than what we typically observe at 1 AU, perhaps because of the higher energy, or perhaps because the longer pathlength has allowed the fluctuations due to small-scale interplanetary structure to be averaged away. The time of maximum (TOM) is calculated from the fit as:

$$TOM = \frac{\sqrt{K_2^2 + 4K_1K_2} - K_2}{2} \quad (2)$$

In most cases, the TOM from eqn (2) is close to the literal TOM in the hourly-averaged *Wind* and *ACE* time-intensity profiles. However, we prefer the fit procedure for two reasons. First, the fitted time-of-maximum interpolates the finite time-binning of the data. Second, and more importantly, given the high statistical precision of the data, the observed time-intensity profiles show a great deal of real, short-term intensity fluctuations, especially at *Wind* energies. These fluctuations probably reflect a variety of convective effects and local structures in the solar wind. The fit procedure provides a systematic, unbiased way of handling this structure while pulling out the underlying trend in the data.

Figs. 2 and 3 show sample fits to the first ∼ 40 hours of *ACE* and *Wind* Fe and O data in the 1997 November 6 and 2000 October 16 SPEs. Arrows mark the location of the TOM, derived from eqn (2). The fits are obviously quite reasonable, except perhaps for *Wind* data in Fig. 2, where the fit does not do a particularly good job in reproducing the rise-phase of the event. Even in these cases, however, the fits deliver reasonable TOMs. Note that in both events, the higher-energy *ACE* ions have shorter TOMs than the lower energy *Wind* ions. More interesting, however, is the variation with species: in Fig. 2 at both energies, O and Fe have nearly the same TOMs; in Fig. 3, on the other hand, the fitted TOMs are different for O and Fe, most clearly at the higher energy.

3 The 1997 November 6 SPE

Fig. 4 shows TTM (defined as the difference between the fitted TOM and the start of the optical flare) *vs.* rigidity in the 1997 November 6 event. The lowest heavy-ion energy

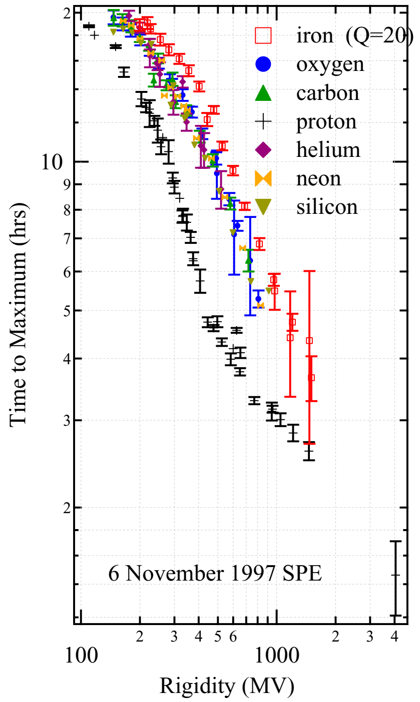

Fig. 4. Time to Maximum plotted versus rigidity for the 6 November 1997 SPE. Fe is assumed to have Q=20, and all other species are assumed to be fully-ionized.

included in Fig. 4 is ~3 MeV/nuc. In this plot, all ions are assumed to be fully stripped, except for Fe, which is assumed to have a charge state of Q_{Fe}=20, consistent with available measurements (Mazur *et al.* 1999) and various modeling efforts directed at this event (Reames *et al.* 1999; Barghouty & Mewaldt 2000; Stovpyuk & Ostryakov 2001). With these assumed charge states, the observed TTMs of various species are tightly clustered, except for Fe and protons.

Particle transport, however, depends upon speed as well as rigidity. In the limit of an impulsive, δ-function particle source at the Sun, Parker (1963) showed that

$$TTM \sim \frac{1}{\beta\lambda} \tag{3}$$

where λ is the scattering mean-free path. In quasilinear theory, the scattering mean free path is expected to have a rigidity dependence $\lambda \sim R^{2-\delta}$, where δ is the power-law index of magnetic fluctuations in wave-number space. Thus, for a Kolmogorov wave spectrum (δ = 5/3), we would expect

$$TTM \sim \frac{1}{\beta R^{1/3}} \tag{4}$$

Fig. 5 shows again the TTMs for this event, this time plotted against $\beta R^{1/3}$. With this modification, the systematic differences among species disappear and the TTM of all species cluster tightly around a common curve. The line in Fig. 5 shows a linear fit to the central portion of the plot, with slope

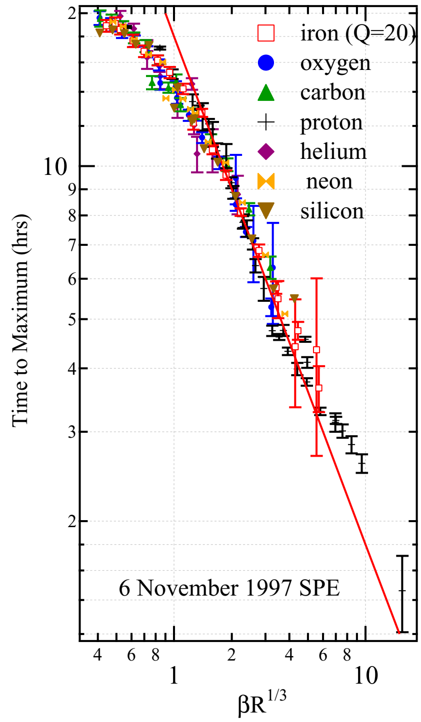

Fig. 5. Time to Maximum in the 6 November 1997 SPE plotted versus β $R^{1/3}$, as discussed in the text. The line is a linear fit to the central region of the plot, constrained to have a slope of -1, as given by eqn (4). The data point from the Climax Neutron Monitor is shown in the lower right corner.

constrained to -1, as indicated by eqn. (4). At lower values of $\beta R^{1/3}$, the locus of points flattens. Note, however, that the line falls close to the high-rigidity datapoint from the Climax Neutron Monitor, in the lower right corner of the plot.

4 Other Events

The TTMs in Fig. 5 present a remarkably simple pattern. It would be a mistake, however, to extrapolate from this one event to a general rule. Figs. 6 and 7 show TTMs vs $\beta R^{1/3}$ in the events of 1998 September 30 and 2000 April 4. Plots are shown for two assumptions about ionic charge states. In the left panel of each figure, all ions are assumed fully-ionized, except for Fe with Q_{Fe}=20 – that is, the same charge states as in the 1997 November 6 event. In the right panels, heavy ions are assumed to have partially-ionized charge states typical of gradual events arising from a solar-wind source population, with Q_{Fe}=11.

In both events, for species lighter than Fe, the locus of points is tighter with the partially ionized charge states. But in both events, both assumptions about the Fe charge state fail to bring Fe into this locus. Fe lies nearer to the other species at higher rigidities, perhaps suggesting energy dependence in the Fe charge states, as discussed by Tylka *et al.* in these proceedings. But no reasonable Fe charge state

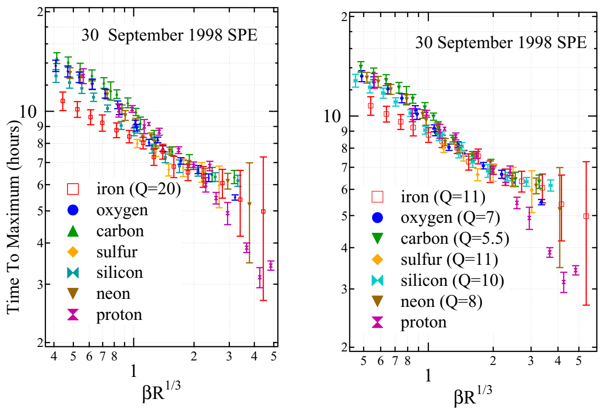

Fig. 6. Heavy-ion TTMs *vs.* $\beta R^{1/3}$ for the 1998 September 30 SPE. The two panels make different assumptions about the heavy-ion charge states, as discussed in the text.

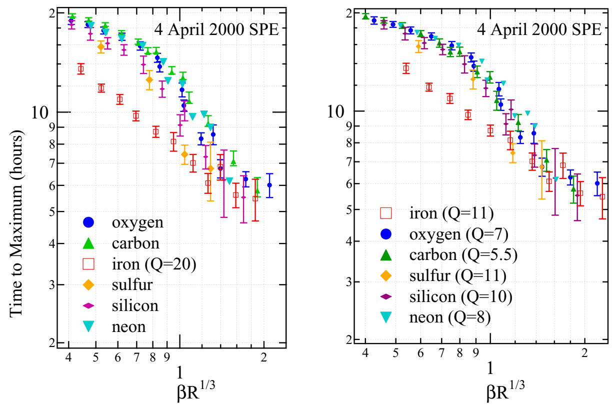

Fig. 7. Like Fig. 6, for the 2000 April 4 SPE. Protons are missing due to an *IMP8* datagap and low rates in *GOES*.

can bring the lower-energy Fe datapoints into the locus of other datapoints. A likely resolution of this conundrum is that TTMs cannot be ordered by a simple scaling parameter like $\beta R^{1/3}$ in these events, and that realistic SEP modeling (Ng et al. 2001) will be needed to understand them.

5 Discussion

In one of the events shown here (1997 November 6), the pattern of TTMs is remarkably simple. Except for the flattening at lower abscissae in Fig. 5, the observed pattern conforms to the simplest model imaginable: an impulsive particle injection at the Sun, diffusing through a Kolmogorov spectrum of magnetic fluctuations. The inverse proportionality between TTM and $\beta R^{1/3}$ in Fig. 5 is probably consistent with a range of injection time-scales, not just the limiting case of a delta-function input. Nevertheless, the accelerator's efficiency must have been significantly greater when it was close to the Sun. Such behavior would also bear upon another puzzling feature of this event: the strongly-energy dependent charge states observed below $\sim$1 MeV/nuc (Möbius *et al.* 1999; Mazur *et al.* 1999) have been taken as evidence for concurrent acceleration and stripping in the low corona (Reames *et al.* 1999; Barghouty & Mewaldt 2000; Stovpyuk & Ostryakov 2001). And yet, this energy dependence does not change over a $\sim$4 day period (Popecki *et al.* 2001). This is difficult to understand if the interplanetary shock is adding substantial numbers of newly-accelerated ions.

The other events we have examined here demonstrate that $\beta R^{1/3}$ is not a universal scaling parameter for TTMs. As previously noted, this should not be unexpected, because of the role of proton-amplified Alfvén waves in these events. (See Ng et al., these proceedings.) Using TTMs to extract ionic charge states is therefore considerably more complicated than suggested by Dietrich & Lopate (1999).

As explained in the Introduction, there are many reasons to believe that TTMs for particles accelerated by CME-driven shocks will not conform to simple scaling laws. Thus, the greater surprise in this study is *not* the events for which no clean pattern emerges in the TTMs, but rather, the event for which it does (1997 November 6). This particular event has proven to be unusual in many respects, and these results suggest that we may not have yet fully understood it. Future work will focus on a comprehensive study of TTMs in many events, to understand what fraction of the events shows simple TTM patterns and why.

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