# On the Solar Release of Energetic Particles detected at 1 AU

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**Abstract.** The 3-D Plasma and Energetic Particles experiment on the WIND spacecraft was designed to provide high sensitivity measurements of both suprathermal ions and electrons down to solar wind energies. A statistical survey of 26 solar proton events has been investigated. For all these proton events, a temporally related electron event is observed. The presented results focus on the properties of protons released near the Sun which show a velocity dispersion when detected at 1 AU. The particle flux onset times observed at 1 AU in the energy range between 30keV and 6 MeV suggest that there are two classes of proton events: (1) For one class (70% of the events), the first arriving protons are traveling almost scatterfree as indicated by the derived path lengths between 1.1 and 1.3 AU, (2) whereas the events of the second class show significantly larger path lengths of around 2 AU. Relative to the electron release time at the Sun, the almost scatterfree traveling protons of the first class of events are release delayed by 0.5 to 2 hours. For the events of the second class, protons and electrons seemed to be released simultaneously within the accuracy of 20 minutes.

## INTRODUCTION

The Wind 3-D Plasma and Energetic Particles experiment (5) has a good temporal resolution for analyzing onset times of solar events at 1 AU. Onset time analysis allow to approximate the coronal release times of the particles observed at 1 AU and it is then possible to relate the in-situ observations to events occurring at the Sun. This helps to understand the acceleration mechanisms of solar energetic particles. Timing analysis of electron events observed by WIND/3DP have been published by Ergun et al. (1) and Krucker et al. (4). ACE/EPAM observations of electron events are discussed in this proceeding by Hawkins et al. (2). In the present work, the timing of proton events is investigated and compared to the electron timing.

## ONSET TIME ANALYSIS

The particle flux onset time at 1 AU, $t_{1AU}(\varepsilon)$, of a particle with energy $\varepsilon$ is given by the particle release time at the Sun, $t_{Sun}(\varepsilon)$ plus the travel time:

$$t_{1AU}(\varepsilon) = t_{Sun}(\varepsilon) + L(\varepsilon)\, v_{rel}^{-1}(\varepsilon) \quad (1)$$

where $v_{rel}(\varepsilon)$ is the component of the relativistic velocity parallel to the magnetic field, and $L$ is the path length. Assuming a simultaneous particle release and a constant path length for all energies ($t_{sun}(\varepsilon) = t_{sun} = const$ & $L(\varepsilon) = L = const$), the observed onset time $t_{1AU}(\varepsilon)$ is a linear function of $v_{rel}^{-1}(\varepsilon)$ with a slope equal to the path length, $L$, and an intersection at the time of the particles release at the Sun, $t_{Sun}$:

$$t_{1AU}(v_{rel}^{-1}(\varepsilon)) \;=\; t_{Sun} \;+\; L \cdot v_{rel}^{-1}(\varepsilon). \quad (2)$$

The onset times at different energies, as well as a lower and upper limits of these values, are determined by eye. The limits are used to describe the uncertainties of the onset times. The error bars shown in the following plots are therefore to be understood as maximum uncertainties.

## OBSERVATIONS

An example of a solar ion event observed by WIND/3DP is presented in Figure 1. The observed velocity dispersion - high energy ions arrive earlier than lower energy ones - shows the solar origin of these particles. The ion flux is found to travel along the magnetic field lines as seen in the pitch angle distribution presented in the bottom two panels of Figure 1.

All ion events presented in this work are proton dominated. This can be proven by the existence of penetrating ions in the 500 to 850 keV electron channels, which can only be explained by penetrating protons. Heavier ions at these energies do not penetrate the foil in front of the electron detectors. Therefore, it can be excluded that the observed ion time profiles are produced by heavier ions than protons, at least for energies between 500 to 850 keV. ACE/ULEIS observations show that the events presented in this work are dominated by protons also at lower energies (J.E. Mazur, private communication).

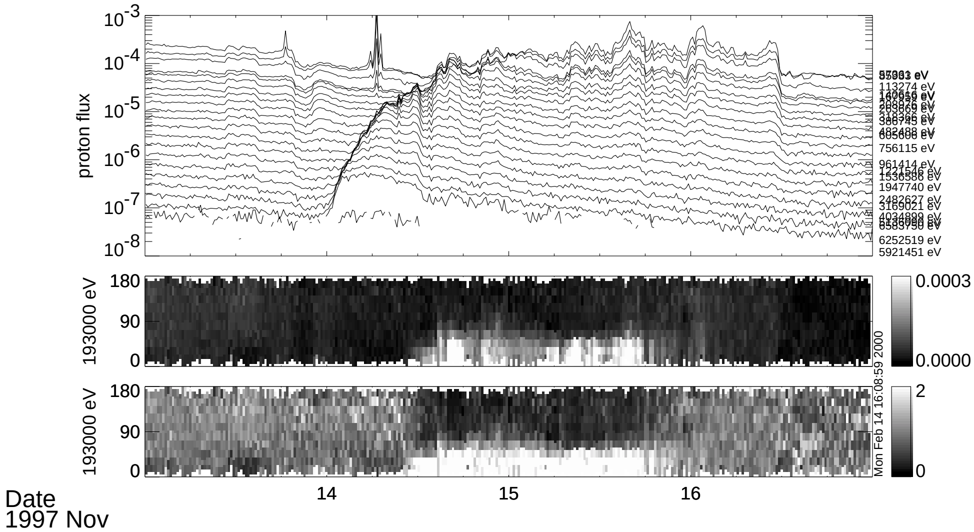


**FIGURE 1.** Overview plot of the proton event on November 13, 1997. Top: The omnidirectional proton flux at different energies is show. Bottom: Pitch angle distribution for 115-279 keV protons. Enhanced flux is shown white. In the bottom panel, the flux values are normalized by the pitch angle averaged flux, whereas the flux in the panel shown above is not normalized.

## ANALYSIS OF TWO TYPICAL EVENTS

Onset time analysis allow to investigate the particle release times at the Sun and the distance traveled until the particles reach the spacecraft (cf. Eq.2). The investigation of these two parameters reveal that there are two classes of events. One event of each class is discussed here in detail followed by a presentation of some statistical results.
An example of the more common class of event (18 out of a total of 26 events) is shown in Figure 2 (left). The linear fits to the onset times as a function of inverse velocity show the same slope for protons (dash-dotted line) and electrons (dashed line) indicating that the first arriving protons and electrons are traveling about the same distance until they reach the spacecraft. The derived path length are $L_p = 1.20 \pm 0.05$ AU for protons and $L_e = 1.19 \pm 0.04$ AU for electrons, respectively. Furthermore, the approximated path lengths are comparable to the Parker spiral length of 1.16 AU calculated from the observed daily averaged solar wind speed. The intersections of the fitted lines give information about the solar release time of protons and electrons. A particle release during the onset of the radio type III burst would give an intersection around zero in the shown plot as indicated by the dotted line in Figure 2. The intersections of the lines fitted to the observed onset times are at later times: The first electrons are found to be released at 14:19$\pm$3UT, i.e. $26 \pm 5$ minutes after the type III onset at the Sun (cf. Krucker et al. 1999), and the first protons seem to be released an additional $54 \pm 12$ minutes later than the first electrons.
An example of the second class of event is shown on the right in Figure 2. The electron onset times give again a similar path length ($L_e = 1.29 \pm 0.13$ AU) as the Parker spiral length (1.26 AU), but in this event, protons seem to travel a much longer distance until they arrive at the spacecraft. The proton path length ($L_p = 2.02 \pm 0.07$ AU) is 60 % longer than the Parker spiral length. Contrary to the previously presented event, the solar release times of protons (21:36$\pm$12 UT) and the electrons (21:26$\pm$3 UT) seem to be simultaneous within the uncertainties. Compared to the type III radio burst onset, both, protons and electrons are again released delayed by 10 minutes or more.

## STATISTICAL RESULTS

Statistical results of the 26 analyzed events are presented in Figure 3. On the left, the derived path length for protons and electrons are compared. There are clearly two classes of events: For one class (18 out of a total of 26 events), electrons and protons have a similar path length, and for the second class (8 out of 26), protons have a significantly larger derived path length than electrons. For events of the first class, there is a linear correlation between $L_p$ and $L_e$, $L_p \propto 0.7 \pm 0.3 L_e$, with $L_p$ general slightly larger than $L_e$. The two classes additionally show

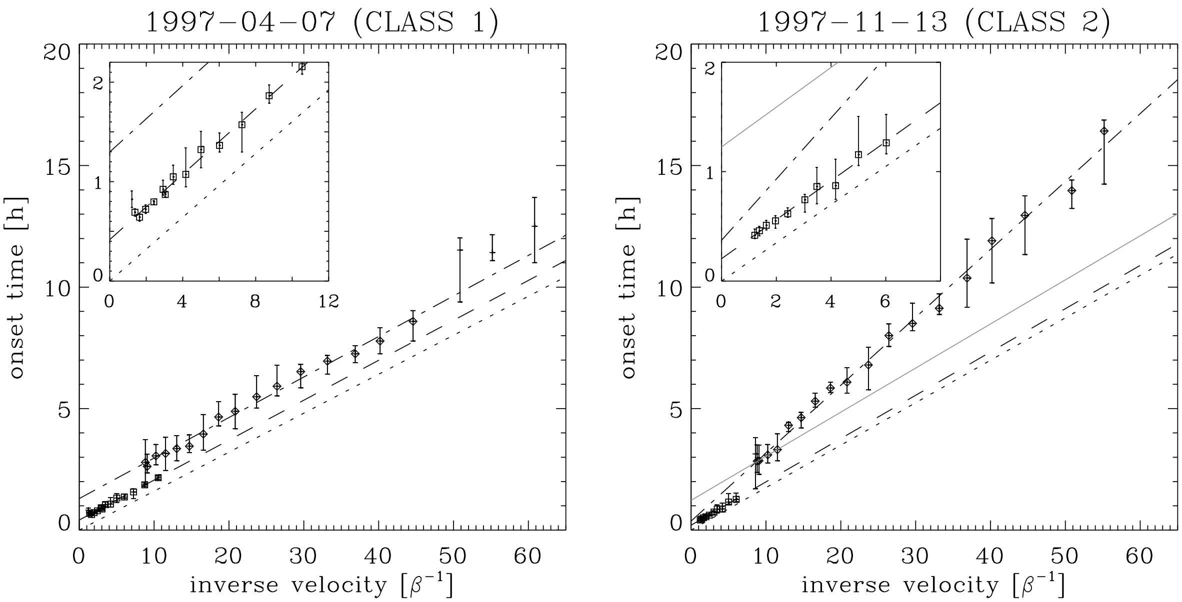


**FIGURE 2.** Comparison of proton (diamonds) and electron (squares) onset times at 1 AU. The onset time after the radio type III burst onset at the Sun as a function of the inverse velocity is shown for two typical events of each class. The dashed-dotted and dashed lines are linear fits to the proton and electron onset times, respectively. The gray solid line in the plot on the right is a linear fit to the >3 MeV proton data only. The dotted lines show the expected onset times for particles traveling scatterfree along the Parker spiral assuming they are released at the time of the radio type III burst onset. The inserts show a zoom-in of the same plots providing a better overview of the electron onset times.

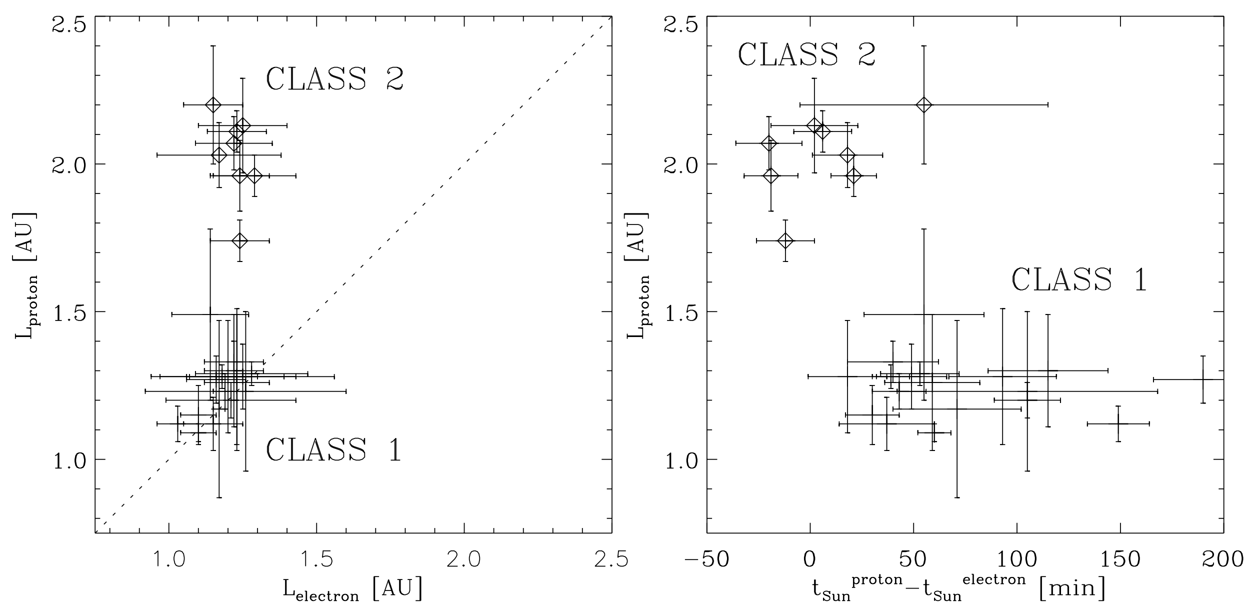


**FIGURE 3.** Statistical results of the onset time analysis. On the left, the path lengths derived from the proton onset, $L_{proton}$, are compared with the path lengths derived from the electron onset, $L_{electron}$. Events with $L_{proton} > L_{electron}$ (class 2 events) are marked with diamonds. On the right, the delay between the proton and electron release times at the Sun, $t_{Sun}^{proton} - t_{Sun}^{electron}$, are plotted against the path lengths derived from the proton onset, $L_{proton}$. Again, events with $L_{proton} > L_{electron}$ (class 2 events) are marked with diamonds.

a different relative particle release for protons and electrons: Events of the first class ($L_p \approx L_e$) show a delayed release time for protons relative to electrons of about one hour, whereas for events of the second class ($L_p > L_e$), protons and electrons seem to be released simultaneously within the uncertainties of about 20 minutes.

## CORRELATION WITH SOLAR FLARES

Within $\pm 2$ hours of the derived solar particle release times, it is very likely to find some solar activity. For the 26 events analyzed, the following numbers of solar events are reported: (i) 21 out of 26 events with a GOES SXR flare, 3 with a possible SXR flare (ii) 17 out of 26 events with a coronal type III burst (Sol. Geophy. Data, SGD) (iii) 25 out of 26 events with an interplanetary type III burst (Wind WAVES) (iv) 15 out of 26 events with a coronal type II burst (SGD) (v) 14 out of 16 with a coronal mass ejection (SoHO/LASCO). A detailed temporal comparison with the derived particle release times, however, does not show a clear correlation with a particular solar event, nor does it show any convincing correlation outlining again the two classes of proton events presented above. In particular, the two classes of proton events do not correspond to the two classes of electron events reported by Krucker et al. (4). They found that one class of electron events is temporally related to radio type III bursts, whereas the other class of event is not. However, the two classes of proton events discussed in this work are not the same classes: Both events presented in Figure 2 show an electron release delayed relative to the radio III burst onset at the Sun.

## CONCLUSION

The onset time analysis presented in this work suggest that there are two classes of solar proton events: (1) one class with $t_{Sun}^{proton} > t_{Sun}^{electron}$ and $L_p \approx L_e$, and (2) the other class with $t_{Sun}^{proton} \approx t_{Sun}^{electron}$ and $L_p > L_e$.

(1) The protons of the first class of events are most likely shock accelerated (cf. 3). Compared to the occurrence of solar events like SXR flares, radio bursts, etc., the proton release time for this class of events is late. At the time of the proton release, the only ongoing event at the Sun is in most of the cases the coronal mass ejection (CME) moving away from the Sun. Therefore, the protons are most likely shock accelerated. Assuming the proton release is related to a shock front of a coronal mass ejection, the late proton release can be interpreted as a release at high altitude. A fast CME shock with a speed of 1000 km/s travels about 5 solar radii within an hour. The observed late proton release might therefore suggest a proton release at several solar radii away from the Sun. LASCO CME observations could corroborate this speculation.

(2) The derived proton path lengths of around 1.5 times the Parker spiral length in the second class of events is rather surprising, especially considering that the first arriving electrons seem to travel along the Parker spiral. It is therefore rather unlikely that protons indeed travel along a much larger distance until they reach the spacecraft. Additionally, the pitch angle distributions during the first hours after the onset are looking similar for both classes of events with a typical width at half maximum of roughly $45^o$. Therefore it is unlikely that some kind of scattering mechanism makes the path length longer for the second class of events. One way to explain the later arrival of the lower energetic protons is that they are released later or that they escape later than the MeV protons. The gray solid line in Figure 2 (right) shows a linear fit to the onset times for proton energies above 3 Mev ($\beta^{-1} < 12$) assuming that the path length is equal to the Parker spiral length. This fit suggests that the $>$ 3MeV protons are released delayed relative to the electron release time as seen in the events of the first class. The later onset time of the lower energetic protons might then be explained by a later release or escape. For 0.3 MeV ($\beta^{-1} \approx 40$) protons, it would be a later release or escape by about 5 hours. Assuming the protons are shock accelerated, the onset times at lower energies could be explained if the shock is releasing the low energetic particle at high altitude only. Another possible explanation for a late arrival of low energetic protons might be that the magnetic connection between the particle release site and the spacecraft might change before the lower energetic and therefore relatively slowly traveling protons arrive (6). The speculation that protons above 3 Mev are released simultaneously (or can escape simultaneously) can be test by analyzing the proton onset times at even higher energies. The onset times at these energies can be used to distinguish between the two linear fits (black and gray line) shown in Figure 2 (left) provided that the accuracy of the derived onset times is good enough. For 50 MeV ($\beta^{-1} \approx 3$) protons, an accuracy of about 15 minutes would be needed.

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