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WIND Observations of Energetic Solar Proton Events Down to keV Energies: Onset Time Analysis

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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 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 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.

1. Introduction

The Wind 3-D Plasma and Energetic Particles experiment (Lin et al. 1995) 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 Krucker et al. (1999). In the present work, the timing of proton events is investigated and compared to the electron timing.
The particle flux onset time at 1 AU, $t_{1AU}(\epsilon)$, of a particle with energy ϵ is given by the particle release time at the Sun, $t_{Sun}(\epsilon)$ plus the travel time:

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

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

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

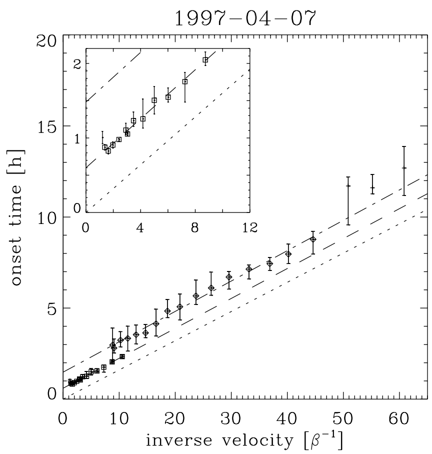

Figure 1. Comparison of proton (diamonds) and electron (squares) onset times at 1 AU. The onset time after the SXR flare onset at the Sun as a function of the inverse velocity is shown for two typical events. The dashed-dotted and dashed lines are linear fits to the proton and electron onset times, respectively. 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 SXR flare onset. The inserts show a zoom-in of the same plots.

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 maximal uncertainties.

2. Results

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 1 (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 soft X-ray (SXR) flare would give an intersection around zero in the shown plot as indicated by the dotted line in Figure 1. The intersections of the lines fitted to

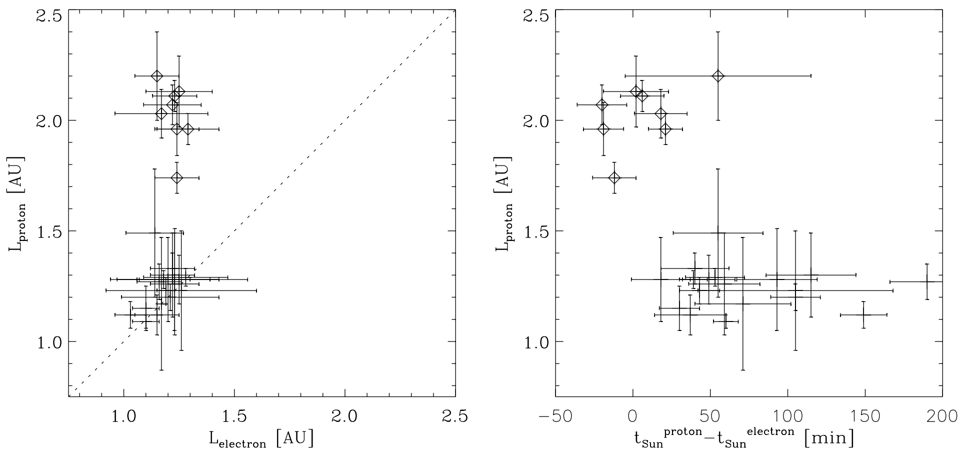

Figure 2. Statistical results of the onset time analysis. On the left, the path lengths derived from the proton onset, L_{proton}, are compared with the path lengths derived from the electron onset, $L_{electron}$. Events with $L_{proton} > L_{electron}$ (class 2 events) are marked with diamonds. On 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.

the observed onset times are at later times: The first electrons are found to be released at 13:19±3UT, i.e. 37 ± 3 minutes after the SXR flare onset at the Sun (cf. Krucker et al. 1999), and the first protons seem to be released an additional 54 ± 12 minutes later than the first electrons.

An example of the second class of event is shown on the right in Figure 1. 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±12 UT) and the electrons (21:26±3 UT) seem to be simultaneous within the uncertainties. Compared to the SXR onset, both, protons and electrons are again released delayed by about 20 minutes.

Statistical results of the 26 analyzed events are presented in Figure 2. 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 a different relative particle release for protons and electrons (cf. Figure 2, left): 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.

3. 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 $L_p > L_e$. These two classes of proton events do not correspond to the two classes of electron events reported by Krucker et al. (1999). They found that one class of electron events is temporally related to interplanetary radio type III bursts, whereas the other class of event is not. However, for both classes of proton events presented in this work, there are electron events related to these proton events with a simultaneously occurring radio type III burst.

The protons of the first class of events are most likely shock accelerated (cf. review by Kahler 1996). 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.

The derived proton path lengths of around 1.5 times the Parker spiral length in some events is rather surprising, especially considering that the first arriving electrons seem to travel along to the Parker spiral. ACE/ULEIS observations show that the presented events are proton dominated. Therefore, it can be excluded that the observed onset times are produced by heavier ions than protons (J.E. Mazur, private communication). Next to the possibility that the protons are indeed traveling a much longer distance than the electrons, it could also be the case that protons at lower energy are released later. Another explanation might be that some mechanism is responsible that even the first arriving protons have an over the path length averaged pitch angle different from zero. A further possibility for a late arrival of low energetic protons is that the magnetic connection between the particle release site and the spacecraft might change before the lower energetic protons arrive. More investigations are needed to understand these surprising new results.

References

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