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Onsets of Solar Cycle 23 Ground Level Events as Probes of Solar Energetic Particle Injections at the Sun

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Abstract

The inferred solar injection times of the first arriving particles of solar energetic particle (SEP) events can be compared with solar eruptive events to provide information on how those particles were accelerated near the Sun. The injection times are best inferred from high-energy electrons and protons with long mean free paths in space. We use the neutron monitor counting rate profiles and space-based near-relativistic electron intensity profiles of the 10 ground level events (GLEs) of solar cycle 23 to determine the initial solar injection times of the SEPs. Those times are compared with microwave, metric and decametric/hectometric (DH) radio bursts and solar CME observations to determine the radiative signatures of early SEP injections. The space-borne solar observations of the current cycle 23 are far superior to those during GLEs of earlier cycles, allowing a more definitive description of solar events at the times of SEP injection. We find that the metric and microwave radio emission onsets always precede the GLE release times, often by tens of minutes; this suggests that the highly relativistic particles are accelerated by a mechanism, probably the CME-driven shock, different from that producing the radio emissions. In half of the 10 events the electron injection preceded the release of the GLE protons, but in the other half the protons were injected before the electrons. The four most intense GLE increases were events where the proton injections preceded the electron injections but still occurred well after the DH type III bursts.

1. Introduction

The acceleration and injection of SEPs at the Sun remains a challenging problem in the studies of SEP events at 1 AU. Because of the time delays due to scattering of the SEPs in the interplanetary medium as they propagate from near the Sun out to 1 AU, it is generally difficult to make definitive associations of high

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energy electron or ion populations with specific candidate solar transient events. The optimum situation for making such associations arises with the occurrence of ground level events (GLEs), for which the detected protons of $\geq$ GeV energies undergo a minimal amount of scattering in the interplanetary magnetic field.

In a study of onsets of 32 GLEs Cliver et al. [1] found typical injection onset delays of $\sim$ 15-20 minutes from Hα onsets and 5-10 minutes from the first significant microwave peaks for the first arriving protons. For three GLEs in 1989, Kahler [3] used a simple propagation model and coronagraph observations of coronal mass ejections (CMEs) to infer CME heights of $\sim$ 2-4 R_o at injection onsets and about 5 to 15 R_o for injection peaks of GeV protons. For impulsive $E >$ 40 keV electron events Haggerty & Roelof [2] and Simnett et al. [4] interpreted the characteristic $\sim$ 10-minute injection onset delays with respect to type III radio bursts in terms of injections at CME-driven shocks with characteristic heights of 2-3 R_o. The onsets of $E >$ 40 keV electron events were also considered in the earlier Cliver et al. [1] study, where it was concluded that they typically precede the onsets of the GeV protons by $\leq$ 5 minutes. The injections of $E >$ 40 keV electrons and GeV protons relative to CMEs were not a part of the that study. The onset injection times of both the $E >$ 40 keV electrons and the GeV protons relative to each other and to flare microwave and CME onsets can now be tested with the more comprehensive observations of GLE events of the recent 23rd solar cycle.

2. The Observations

The relevant observations are given in Table 1, with all times relative to the "Earth-received times" of the radio and CME data at 1 AU. For each event we list first the neutron monitor station and observed GLE onset time, then the inferred injection time at the Sun for the GeV protons and the percent increase of the GLE above background. The inferred proton injection times, and also the inferred DE4 175-315 keV electron injection times of the next column, result from adding 8.2 minutes to the derived solar injection time taken back to the Sun. The electron injection times for the DE4 channel of the ACE EPAM instrument were deduced by assuming a path length of 1.2 AU and an average electron speed of 0.73c [2], resulting in a subtraction of 13.7-8.2 = 5.5 minutes from the observed onset times. The next column gives Δt, the inferred electron onset time minus the inferred proton onset time, where positive values mean that the protons were injected before the electrons. Onsets of 2.7 GHz and metric type II bursts of the next two columns were taken from reports in Solar-Geophysical Data. The onsets of the decametric-hectometric (DH) type III bursts were obtained by one of us (MR), usually at 14 MHz, by inspecting the emission plots from the Wind/WAVES radio experiment. The CME liftoff times from 1 R_o were obtained by one of us (GS) from height-time plots of the CME leading edges. These times were compared

Table 1. Event UT Onset Times for the 10 GLEs of Solar Cycle 32

GLE Date	Stat.	GLE Obs.	Onst Infr.	Pct Inc.	DE4 Infr.	Δt	2.7 GHz	Typ IIm	Typ III	CME 1 $R_\circ$
06/11/97	Oulu	1210	1207	10	1215	8	1151	1153	1153	1154–
02/05/98	Oulu	1356	1353	8	1343	–10	1337	none	1335	1340
06/05/98	Oulu	0830	0827	2	0803	–24	0801	0803	0801	0736+
24/08/98	SPol	2341	2238	2	2228	–10	2157	2202	2204	NA
14/07/00	SPol	1034	1031	60	1033	2	1004	1017	1023	1025
15/04/01	SPol	1357	1354	230	1359	5	1333	1347	1349	1342–
18/04/01	SPol	0233	0230	27	0237	7	0213	0217	0215	0159+
04/11/01	SPol	1655	1652	3	1635	–17	1602	1610	1613	1615
26/12/01	Oulu	0539	0536	7	0526	–10	0438	0459	0513	0502
24/08/02	Apty	0123	0120	4	0123	3	0050	0101	0100	0103

with other similar measurements by one of us (SK). If the other liftoff times were somewhat ($\geq$ 5 min) earlier (later) than the time given, we appended a – (+) symbol to the CME liftoff times of Table 1.

3. Analysis

We have studied 10 GLEs from the last solar cycle which resulted in high latitude neutron monitor increases ranging from around 230% (15 April 2001, South Pole) to around 2% (6 May 1998, Oulu). Note that a typical diurnal variation is around 1%. When we compare the relativistic particle onsets, we find that for five events, which include those with the four largest percentage increases, the protons appeared to be injected before the electrons. The maximum time difference was 8 minutes, and we estimate the uncertainties to be around +/– 2 minutes. For the other five events, which all have small increases, the electrons preceded the protons by around 10-20 minutes. The X-ray and optical flares which were associated with the GLEs were predominantly GOES X-class (8 of 10) and Hα 3B or 2B (6 of 10), with one (18 April 2001) and possibly a second (24 August 2002) behind the west limb.

The GLE proton onsets were delayed by roughly 20-30 minutes relative to the 2.7 GHz and other radio onsets. Significant delays of the order of 20 minutes also occurred relative to the CME lift-offs. We have calculated the average CME leading-edge heights at the times of GLE proton injections to be about 2.7 $R_\circ$, in reasonable agreement with the CME heights of Kahler [3] for three GLEs in 1989.

The 175-315 keV electron onsets typically follow the CME onsets, in agreement with the results of Simnett et al. [4]. However, only one of the events in our study created a strong electron beam at the ACE spacecraft, which was the criterion for inclusion in their analysis.

4. Conclusions

Cliver et al. [1] noted that in some cases the relativistic protons were injected very near the flash phase of the flare, and that in several events a model for prolonged acceleration times $\sim$ 15 minutes is unlikely. Further, they stressed that the relativistic electron injection followed the GeV protons by more than 5 minutes. Half our events are consistent with this result, and the interpretation of the majority of the remaining events may be influenced by the low intensity of the GLE, which would tend to give a later time for the proton injection.

We have compared the GLE onsets with the DH type III onsets and find that the GLE onsets are always later. For the four GLE events with $\geq 10\%$ increases we find that the GLE onset times are later than the DH type III onsets by 5 to 15 minutes. However, the onsets of the weaker GLEs are much later, from 18 to 39 minutes. This also suggests that the later times of the weaker GLEs may be a threshold effect. We note that if we assume that this time difference should also be in the same range as for the strong events, i.e., 5 to 15 minutes, then most of the weak GLE onset times would precede those of the electrons. We also note that the DH type III onset times are usually within a few minutes of the onset of the 2.7 GHz radio events.

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