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Timing of the relativistic proton acceleration responsible for the GLE on 20 January, 2005

G.M. Simnett^a and E.C. Roelof ^{b}

(a) School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, UK
(b)Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723, USA
Presenter: G.M. Simnett (gms@star.sr.bham.ac.uk), uki-simnett-G-abs2-sh15-oral

The ground level solar proton event of 20 January, 2005 had a rise to maximum of around 5 minutes, with a similar decay time to 1/3 maximum. This suggests that the magnetic connection from the Sun to the Earth was good and that the proton injection was impulsive on the timescale of a few minutes or less. Comparison of the proton onset time with the solar electromagnetic emissions which accompany large flares, together with observations of the coronal mass ejection (CME) seen around the injection time suggests that the CME was not responsible for the relativistic ion acceleration. The near-relativistic (175-300 keV) electron intensity onset at $\sim$1 AU was some 7-8 minutes later than the proton onset. Implications of this on the relative injection time or the path length traversed by the particles is discussed.

1. Introduction

The exact physical processes involved in powering large solar flares remain enigmatic. In part, the one of the unknowns is the acceleration of the most energetic particles, namely the protons of energies above $\sim$1 GeV. If protons of these energies are produced with a high enough intensity, then on reaching the Earth, a ground level event (GLE) is initiated which may be detected by a the network of neutron monitors around the Earth. In this paper we address the precise timing of relativistic proton acceleration in the flare of 20 January, 2005.

The counting rates of the neutron monitors operated by the Bartol Research Institute, University of Delaware are shown in Figure 1 covering the main part of this event (Data courtesy of Professor J.W. Bieber). The event is clearly very anisotropic. The south polar neutron monitor recorded the largest increase, which began no later than 06:49 UT and took around 5 minutes to reach maximum. Other stations such as Thule, Greenland, observed an increase less than 5% of the south pole, with the maximum delayed by 37 minutes. However, other northern latitude neutron monitors showed an impulsive increase similar to the South Pole. The Climax, Colorado, neutron monitor intensity-time profile had a rise to maximum from the background level, and decay to 1/3 maximum intensity covering just 7 minutes, compared to 10 minutes for the south polar monitor.

In general, observations of delays in the injection of protons from, say, the hard X-ray maximum, cannot be used definitively to establish acceleration time, as there are propagation and trapping considerations. These can only add to any delay. Thus the most definitive observations come when delays are small. We believe that the 20 January 2005 flare event is one where trapping and propagation effects related to the onset are minimal. Thus this event is ideal to provide hard constraints on the timing of relativistic proton acceleration in flares.

The primary question we wish to answer is when the energetic protons responsible for the ground level event were accelerated. The secondary question is whether the coronal mass ejection(CME) accompanying the flare was in any way controlling their acceleration or release.

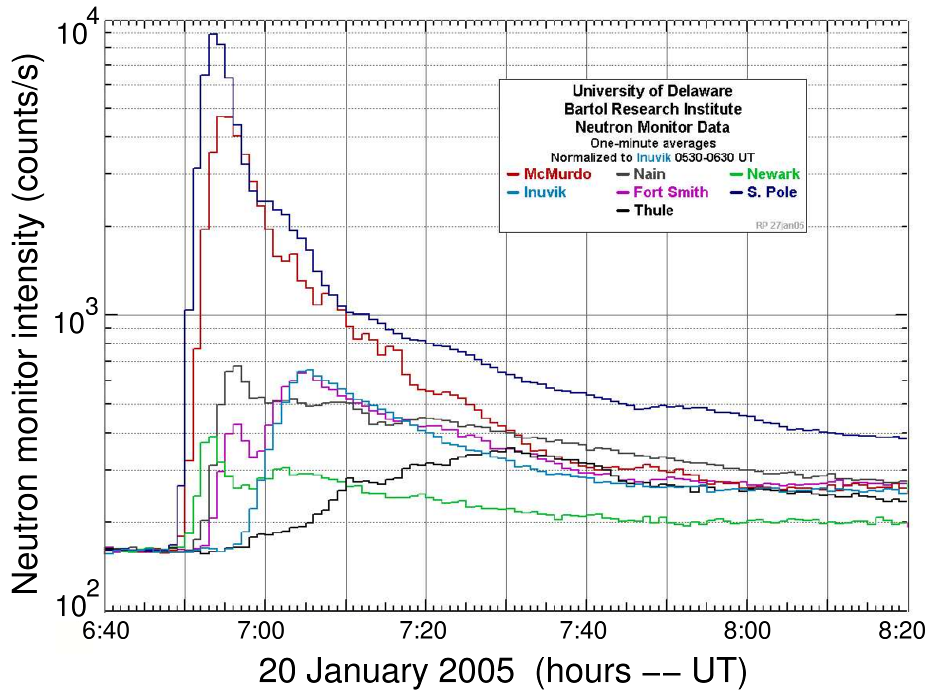

Figure 1. The counting rate recorded by neutron monitors from the Bartol Research Institute on 20 January, 2005.

2. The Electron and Solar Observations

The event we are discussing was a GOES class X 7.1 flare, optical class 2B, from an active region at N12 W58 on the visible solar disc. The hard X-ray (HXR) maximum seen by RHESSI was around 06:46 U T ± 1 minute, while the maximum in the 0.8-7.0 MeV channel, which includes the neutron capture line at 2.223 MeV, was around 06:47 UT (Dr B.R. Dennis, private communication). The 4-7 MeV gamma ray burst , which includes prompt gamma ray lines of C and O, in addition to any continuum present, started at 06:44 UT and was a maximum at 06:46 UT (Dr G.H. Share, private communication). The high energy signatures of the event started at 06:35 UT. An intense microwave burst was produced which reached at least 53000 10^4 Jansky at 15.4 GHz at 06:44 UT. Although the soft X-ray (SXR) event had a long, low level decay, the duration (full width at 1/10 maximum) was less than 30 minutes. Thus this event is an excellent example of an intense, impulsive very energetic event which released highly relativistic particles into the interplanetary medium.

It has been shown [1] that the injection of near-relativistic electrons is typically delayed ∼10 minutes from the decametric type III radio emission which is normally observed for such events. Furthermore, the electron injection is shown to be associated with CMEs, and to take place when the CME was around 2-3 $R_\odot$[2].

In Figure 2 we show the ∼175-∼300 keV electron intensity for the three electron telescopes of the EPAM instrument [3] on the ACE spacecraft (see Figure caption). The electron onset appears first at 06:57 UT in the backward facing telescope, but this is probably because the magnetic field at the time had a strong northward component. When projected back to the Sun, for a nominal 1.1 AU propagation path and a velocity of 0.75c, this gives an release time of 06:45 UT at the Sun. A similar analysis for the relativistic protons gives a release time of 06:39 UT.

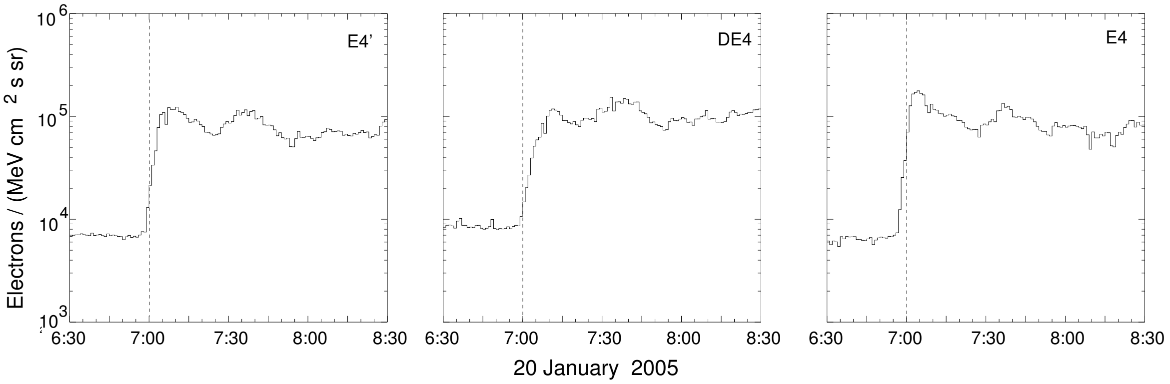

Figure 2. The ∼175-∼300 keV electron intensity for the peak sector in the LEFS60 (E4′ sector 3), the deflected electrons (DE4 sector 2) and LEFS150 (E4, sector 4) telescopes from 06:30-08:30 UT on 20 January. The data are plotted at a time resolution of 1 minute. A dashed line is drawn at 07:00 UT, to aid the eye. See [3] for definition of the EPAM instrument.

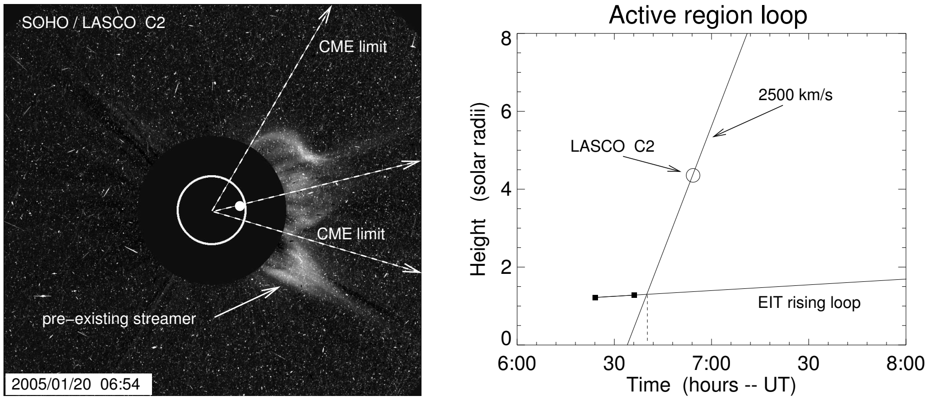

Figure 3. Left panel:The image from the LASCO C2 coronagraph at 06:54 UT on 20 January. The outermost dotted lines are the suggested angular limits to the CME, projected back to the centre of the Sun. The white circle represents the photosphere and the black disc represents the position of the C2 occulter at around 2.2 $R_\odot$. The solid white circle is at the position of the active region from which the flare erupted and the middle dashed line is a radial line through this position. Right Panel:The EIT rising loop and the C2 image, put together as a suggested height-time plot.

The flare produced a fast CME off the solar west limb and the coronagraph image from SOHO/LASCO [4] at 06:54 UT is shown in Figure 3 (left panel). Only one image of this CME was taken because the detector was swamped with charged particles by the time of the next exposure. EUV images of the flare region were obtained by SOHO/EIT [5] which showed a slowly rising loop structure. This subsequently erupted along the central dashed line shown in Figure 3. In the right panel we have shown the height-time plot of this looptop, and the position of the leading part of the CME. If we suppose that the CME has a speed of 2500 km s^{-1}, then the onset was around 06:40 UT, or 06:32 UT at the Sun.

The differential energy spectrum, $dJ/dE \propto E^{-\gamma}$, of the electrons from this event was very hard, typically with $\gamma < 1.5$. This is more usual for electrons associated with a major flare than with CME-shock acceleration [6].

3. Discussion

The onset of the electrons at ACE was at 06:57 UT and they were propagating along the magnetic field. Assuming no scattering (consistent with the observed pitch angle distribution) they would have left the Sun at 06:45 UT. At this time the CME would have been at around 3-4 $R_\odot$. The relativistic protons left the Sun at 06:39 UT, ∼6 minutes before the electron injection. It is unlikely that propagation of the two species in the interplanetary medium was other than scatter-free. The electron intensity remained high for several hours, which is in complete contrast to that of the relativistic protons. We therefore believe that the GLE protons were accelerated with a process related to the GOES class X7.1 flare rather than the CME-driven shock. The observation of intense γ ray lines from the flare indicates that energetic protons were present. Most of the electrons were probably also from the flare, as they had a hard spectrum. The erupting magnetic structures (the CME) delayed the release of the particles until the CME had reached several $R_\odot$. We postulate that the turbulence around the shock was able to contain the low rigidity electrons for much longer than the relativistic protons. The long duration of the electron emission could be a mixture of continued release of trapped flare electrons behind the CME plus some CME-shock acceleration. However, the latter is not needed to explain the observations in a plausible manner. The injection of the protons was clearly very short lived, and was thus inconsistent with CME-shock acceleration, as this would not stop rapidly, which would be needed to match the very fast decay of the proton intensity. The residual, essentially isotropic, decay of the relativistic protons may reflect containment within the inner heliosphere by virtue of a scattering boundary beyond 1 AU [7, 8].

The conclusion we reach is that the protons responsible for the ground level neutron monitor event and those electrons detected by ACE/EPAM with a very hard spectral index were accelerated in a process or processes directly related to the solar flare, and were not accelerated by the CME. However, the CME was probably responsible for delaying the release of the flare electrons by ∼6 minutes, relative to the protons, onto magnetic field lines connected directly to ACE. The timing of the various emissions, the short duration of the relativistic proton event, and the electron energy spectrum are the most critical pieces of evidence for this conclusion.

4. Acknowledgements

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