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Two acceleration mechanisms for ground level enhancements

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Abstract: The previous paper, [1], suggested that particles in the 20 January 2005 GLE were probably accelerated in two distinct regions. The anisotropic distributions and time profiles in two such ephemeral GLEs in 1960 and 1978 were similar. This paper uses the 300 KeV gamma ray images obtained by RHESSI to provide evidence for the acceleration of the first, highly anisotropic pulse low in the corona. It is shown that such initial ephemeral enhancements have been observed in at least 9, and perhaps 11 previous GLEs associated with western flares. This leads us to propose that the 20 January 2005 event is a defining example of the GLE, namely that there are two separate acceleration episodes: (a) acceleration directly associated with the flare itself in the lower corona, and (b) acceleration by a supercritical shock driven by the associated CME, at about 2.5 solar radii.

Introduction

The previous paper, [1], has shown that the GLE of 20 January 2005 can be resolved into two components with substantially different characteristics. Pulse P1, commencing at 06:49:45±15" was short-lived, field-aligned, highly anisotropic, and had a hard spectrum. Pulse P2 was longer-lived, much less anisotropic but still field-aligned, it had a softer spectrum, and started ~ 8 minutes after P1, at 06:57:30±30". P1 had little radiation with pitch angles > 120°, while P2 contained a significant number of cosmic rays with much larger pitch angles from its onset. In addition, P1 was primarily due to particles of up to 5 GV rigidity, and essentially free of velocity dispersion. It therefore provides the most direct information about the near-Sun injection process.

High energy solar observations

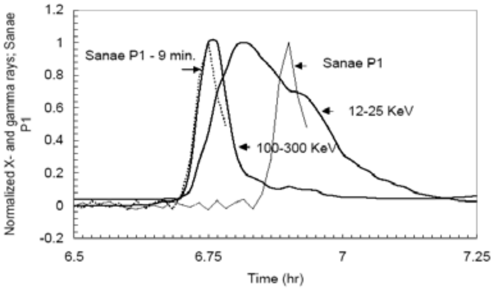

Figure 1: Profiles of 12-25 KeV and 100-300 KeV X- and gamma rays, and the Sanae P1 pulse.

The GLE was associated with a GOES Class X7.9 solar flare that erupted at 06:36 at 14°N and 67°W. The RHESSI spacecraft observed X- and gamma-ray bursts from 2.5 KeV up to 17 MeV. Figure 1 shows the 12-25 KeV and the 100-300 KeV channels, together with the Sanae P1 pulse. Figure 2 displays selected images of the event by the RHESSI imaging spectrometer, revealing the following time sequence: The 12-25 KeV X-ray flux started to increase at ~ 06:34:30 {06:26:10 at the Sun; all times are in UT}, it rose to a maximum at ~ 06:49:00 {06:40:40}, and fell slowly thereafter. The top series of images in Figure 2 for this energy interval shows that the emitting region was initially centred at about 14ºN and 65ºW. The behaviour at higher photon energies was distinctly different, e.g. there was little variation in the 100-300 KeV flux until ~ 06:43:00 {06:34:40} when it rose rapidly to a peak at ~06:45:00 {06:36:40}, and then fell almost as rapidly, attaining its 50% level by ~ 06:47:00 {06:38:40}. The bottom sequence of Figure 2 shows that this short-lived gamma-ray pulse originated 5º to7º East of the source of the 12-25

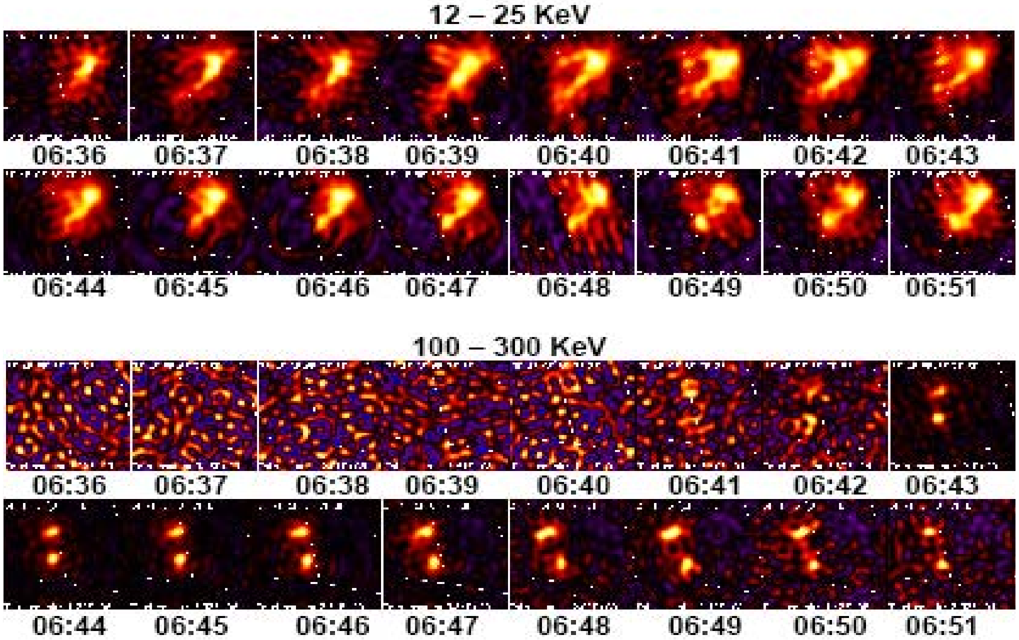

Figure 2: A series of X-ray and gamma-ray emission pictures form the sun as observed by RHESSI, in the vicinity of ~ 15 °N and 60° W. Times are observation times at Earth in UT.

KeV X-rays, and consisted of two intense emitting regions, each of angular extent < 2º. Up until 06:39:00 {06:30:40} all of the 12-25 KeV emission was centred on 65ºW, with little emission near 60º W. Starting at 06:39:00 {06:30:40}, the 12-25 KeV emission region at 65º W extended in a loop-like structure that terminated in two bright spots at ~60º W. In the subsequent three minutes, these spots intensified greatly, becoming consolidated at 12º N, 58º W, and 15º N, 60º W. These spots developed later in the 100-300 KeV images. The loop-like emission and the two bright spots ~ 7º East of the initial emissions lead us to the view that the low-energy X-ray emission was initially from a considerable height in the corona (~ 0.3 R_s), and that at ~ 06:39:00 {06:30:40} the emitting region extended down the magnetic field lines into the chromosphere. The field-aligned nature indicates that the emissions were due to charged particles interacting with coronal gas nuclei. The loop-like nature and the bright spots remained intact until after 06:51:00 {06:42:40}.

The origin of pulse P1

The higher-energy gamma rays of 100-300 KeV are consistent with the presence of a short-lived population of high-energy cosmic rays trapped in the coronal field for > 10 minutes, starting at 06:43:30 {06:35:10}. Thus, the cosmic rays would collide with coronal gas, and emit prompt gammas from the $^{12}C(p,\gamma)$, $^{16}O(p,\gamma)$, and other nuclear reactions. Figure 1 shows that the 100-300 KeV gamma-ray pulse and the P1 pulse from Sanae have very similar durations and profiles. Shifting the Sanae response 9 min. earlier (i.e. assuming a Sun-Earth propagation time of 17:20 minutes) shows that there is a remarkable agreement between the characteristics of the pulses - both the rise and fall phases are similar, as is the short-lived nature of peaks. This agreement in shape of the gamma-ray and Sanae P1 pulses shows that pitch-angle scattering was a minor contributor to the P1 pulse shape at Earth.

We therefore propose that pulse P1 and the emission of high-energy gamma rays from the two spots in Figure 2 were both direct consequences of the presence of the same population of cosmic rays at the Sun; they are, in fact, two essentially equivalent, but independent observations of the P1 solar cosmic-ray population.

The top diagram of Figure 3 shows our proposed model for the origin of P1. Relatively low-energy protons and electrons were first accelerated in close proximity to the region where the flare erupted at ~ 06:36 {06:28}, leading to the dispersed X-ray emissions from high in the corona. The loop-like structure at 06:40 {06:32} indicates that the sunspot magnetic fields had not yet ruptured, and that they were being filled with newly accelerated solar cosmic rays. Relativistic protons were then first accelerated at about ~ 06:43 {06:35}, and they spiraled in both directions along the sunspot field to low coronal altitudes, where they interacted with the higher coronal matter density to create the two intense sources of high-energy gamma rays. At these points they would be in relatively intense magnetic fields of ~800 G, [2], where there would be strong magnetic gradients, and probably considerable magnetic turbulence due to Alfvèn waves. These would result in rapid scattering and diffusion of the solar cosmic rays to adjacent open field lines low in the corona. The field would be ~10 G on the periphery of the active region, and adiabatic focusing would reduce the pitch angles to < 10º when the particles reached the nominal commencement of the HMF at 2.5 R_S. As discussed in the previous paper, [1], this would result in this population of particles traveling to Earth in a relatively scatter-free manner, arriving here in a highly anisotropic beam.

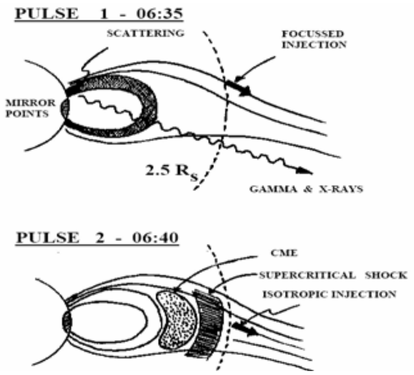

Figure 3: Proposed two-step GLE acceleration model

The origin of pulse P2

This pulse commenced at ~ 06:57:30. Allowing for the propagation time of 17:20 min. determined for P1, the P2 particles started to leave the Sun at {~06:40}, when the loop-like structure was still intact. Unlike for P1, there was no synchronous enhancement in the high-energy gamma-ray emissions, suggesting that the P2 population had no direct magnetic connection to the higher densities in the lower corona. Based upon the discussion in the previous paper, [1], the mild anisotropy of P2 is explicable in terms of the P2 particles being injected into the HMF much more isotropic, so that the majority of them suffered substantial pitch angle scattering en route to Earth, as dicussed in [1].

It was shown by [2] that the Alfvén velocity drops from >1000 km/s near a large sunspot group to ~ 200 km/s at $R \approx 1.5$ R_s.. It then increases steadily to ~ 700 km/s near $R_s = 3.5$, and then falls steadily again. They authors suggest that coronal shocks can attain super-critical velocities in the ranges 1.2 - 2.9 R_s, and > 6.0 R_s. Ions will be accelerated to cosmic ray energies in such a supercritical shock, and they suggest that solar cosmic rays would be accelerated in both regions.

RHESSI data were used by [3] to estimate that the CME associated with the flare of 20 January 2005 lifted off at 06:40 {06:32}, and was traveling at ~ 2500 km/s = 0.2 R_s per min. We concluded above that the first of the P2 cosmic rays left the Sun at ~06:40. Based on these estimates, the CME would then have been at < 2.7 R_s, and in the inner region of low Alfvén velocity. For a CME velocity ~ 2500 km/s, the Alfvén Mach number would have been 5 to 6, and efficient acceleration of ions would be expected to occur in a supercritical shock traversing this region. The particles would escape into the HMF, ahead of the shock in a relatively isotropic manner as shown in the lower part of Figure 3, and would suffer significant pitch-angle scattering en route to Earth.

Thus, the 20 January 2005 observations are explicable in terms of acceleration in two different regions of the corona, as in Figure 3. Relatively low-energy protons and electrons were first accelerated in close proximity to the region where the flare erupted low in the corona, leading to slowly increasing, dispersed X-ray emissions.

Relativistic protons and electrons were first accelerated at ~ 06:34:45, and they spiraled in both directions along the sunspot magnetic field to low coronal altitudes, where the protons interacted with the higher coronal matter density to emit intense gamma rays. The cosmic rays also diffused onto adjacent open field lines, and adiabatic focusing in the corona meant that they were injected into the HMF with low pitch angles and consequently reached Earth rapidly in a highly anisotropic pulse. The shock ahead of the CME, associated with the flare, developed in the region of low Alfvén velocities at ~ 06:40, and commenced to accelerate relativistic particles. These escaped ahead of the shock into the HMF in a relatively isotropic manner, and then suffered pitch-angle diffusion to reach Earth in a slowly rising, mildly anisotropic pulse of radiation.

There is an extensive body of work that shows that there are two sources of solar cosmic rays for solar energetic particle (SEP) events, as summarized in [4]. The first class contains the "rapid" events seen by spacecraft and exhibit highly anomalous ratios between the fluxes of ^{3}He and ^{4}He. We propose that this class of low-energy SEP corresponds to the pulse P1 analyzed herein.

Similar Events in the Past

In the past, lower time resolution on neutron monitors might not have been able to distinguish pulses P1 and P2 in an unambiguous manner.

We have examined the historical record to identify GLEs that either show at least one neutron monitor with an ephemeral pulse similar to P1, or at least show a clearly defined difference in onset times between several neutron monitors. Table 1 lists 10 large GLEs with these characteristics, in addition to that of 20 January 2005. Note in particular that 9 out of 11 do exhibit short ephemeral pulses similar to P1. The localized nature, the fast rise and fall times, and the short durations all indicate that the ephemeral pulses were strongly anisotropic, as for 20 January 2005. In particular, the anisotropic character was essentially identical for the three P1 events 3, 5, and 11 in 1960, 1978, and 2005, that occurred at substantially different phases of the solar cycle. This suggests that the anisotropy of the P1 pulse is little affected by changes in the scattering properties of the HMF throughout the solar cycle.

Table 1

List of 11 GLEs that show a P1, P2 double pulse character similar to the one of 20 January 2005. δt is the onset time difference between P1 and P2 (min.). N is the number of stations that saw P1.

No.	ddmmyy	δt	P1	N	Position	Amp. %
1	070342	8	y	1	west limb	4000/1500
2	230256	9	n	-	N25, W85	?/>3000
3	040560	3	y	7	N10, W90	300/?
4	151160	30	y	2	N25, W35	160/80
5	070578	<5	y	10	N24, W68	215/?
6	221089	15	y	3	S27, W32	200/20
7	241089	14	n	-	S29, W57	?/110
8	151189	10	y	1	N11, W28	12/3
9	210590	10	y	2	N34, W37	20/5
10	240590	30?	y	2	N36, W76	50/7.5
11	200105	8	y	4	N12, W58	2900/300

Conclusions

We conclude that many past GLE have exhibited P1 and P2 pulses similar to the one on 20 January 2005, and we propose that this event should be regarded as the defining example of the GLE. The P1 and P2 pulses are due to two separate acceleration episodes in the typical GLE: (a) acceleration directly associated with the flare in the lower corona, and (b) acceleration by a supercritical shock driven by the associated CME, at ~ 2.5 R_s.

Acknowledgements

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