The Ground Level Enhancements of Solar Cycle 23

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***Abstract*. In a recent paper, McCracken et al. [1] pointed out that the Ground Level Enhancement of 20 January 2005 may have been produced by more than one acceleration mechanism, with the first acceleration being directly associated with the solar flare and the second one with the CME associated with that event. That paper also noted several other GLEs with similar multiple pulse structures. This paper systematically investigates all the GLEs of solar cycle 23, from GLE 55 on 6 November 1997 to GLE 70 on 13 December 2006, to study their morphology and pulse structure. We use all the data of all NMs that saw each event, to have as much anisotropy and spectral information as possible. Three of these 16 events do contain such double-pulse structures.**

***Keywords*: solar cosmic rays, ground level enhancements, NMs**

I. INTRODUCTION

Seventy so-called ground level enhancements (GLEs) have been recorded since 1942, mainly by the worldwide network of neutron monitors (NMs). These GLEs are at the high-energy end of the of the solar energetic particle (SEP) spectrum, and hence they represent the strongest acceleration episodes on the sun. NMs are particularly well-suited to record these GLEs because their high counting rate leads to high statistical significance of the increases, and excellent directional sensitivity can be achieved by considering the increases seen by all 40-odd NMs together.

Originally, the source of SEPs was ascribed to acceleration in solar flares, but during the last ∼30 years the consensus has formed that the bulk of the acceleration is due to stochastic first-order Fermi acceleration by the bow shock of the coronal mass ejection (CME) that often accompanies such a flare.

In a recent paper, McCracken et al. [1] pointed out, however, that GLE number 69 on 20 January 2005 may have been produced by more than one acceleration mechanism, with the first one likely being the solar flare, and the second one the CME shock. The arguments were mainly based on the promptness and strong anisotropy of the first pulse (P1), as opposed to a much less anisotropic and more gradual second pulse (P2). The case for a double acceleration mechanism was further supported by a sudden (within one minute) softening of the spectrum as seen by the combination of the Sanae NM and neutron moderated detectors. These two detectors have different energy responses, and the combination was unique for this event because they saw the two pulses with roughly the same size. That paper also noted 10 out of the 22 large (> 20%) GLEs in the historic record had similar double-pulse structures.

These observations, and the inferences made from them, formed part of the motivation for a Coordinated Data Analysis Workshop (CDAW) in January 2009 on the GLEs of solar cycle (SC) 23. The purpose of the workshop and its working group is to compile a comprehensive data set of these GLEs, together with the various electromagnetic signals of the active regions, flares and CMEs that accompany them. In this context this paper gives an overview of the 16 GLEs of SC 23.

II. THE GLES OF 20 JANUARY 2005 AND 13 DECEMBER 2006

We first discuss the properties of a single GLE. In [1] we used GLE 69 of 20 January 2005 to highlight the two-component features. Here we use GLE 70 of 13 December 2006 instead as an example. It is the last one that was observed, and several reports ([2], [3], [4], [5], [6], [7]) about it were presented at the previous ICRC in 2007, and also by [11].

This GLE was about 50 times smaller than GLE 69, but it showed the same double-pulse features. P1 was observed by only seven NMs, shown in Figure 1. These monitors have asymptotic directions that put the axis of symmetry of this anisoptropic population in the vicinity of 100°E, and latitude near the equator (geographic). P2 is shown in Figure 2, and it was clearly much less anisotropic because it was seen by many more NMs with a similar amplitude. Exceptions are Barentzburg, which shows indications of P1 in its fast rise time, and Sanae, which has a higher increase than the rest because it is the only polar NM at a high altitude. P1 also had a much shorter rise time (≈ 5 min. instead of ≈ 30 min.), and it was shorter than P2 - it became submerged below P2 after ≈30 min.

An important difference with GLE 69 is that in this case P1 has considerable structure. Oulu and Apatity have ’normal’ peaks, but Mawson shows a substructure of two peaks, which may also explain the flat response of Kerguelen (in 5-min. resolution). A generally accepted explanation for a double-pulse nature of GLEs is that it can be caused by propagation effects in the heliospheric magnetic field. Such an explanation only needs one acceleration mechanism, by implication the CME shock. Two examples of such propagation effects are that P2 may be the reflection or back-scattering of pulse 1 from a magnetic barrier beyond 1 AU, e.g. [9], or that the two pulses arrive at Earth via the opposite legs of an extended

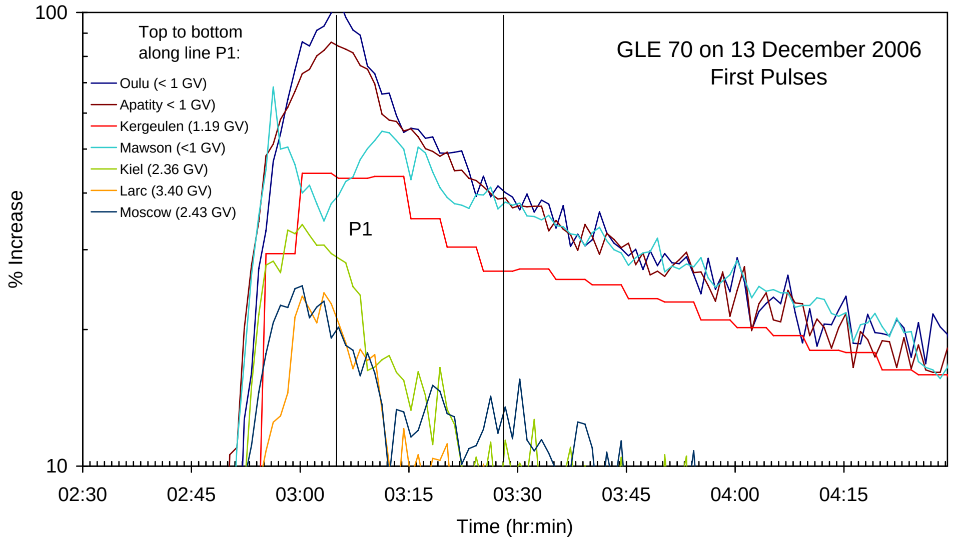

Fig. 1. Pulse 1 of GLE 70 on 13 December 2006. The peak times of pulses 1 and 2 are marked with vertical lines.

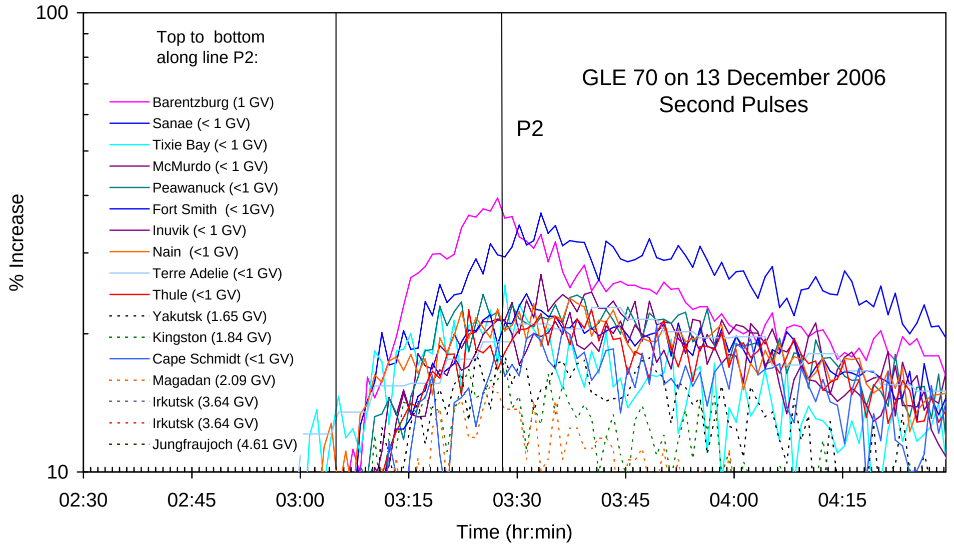

Fig. 2. Pulse 2 of GLE 70 on 13 December 2006. The peak times of pulses 1 and 2 are marked with vertical lines. NMs with cutoff rigidities $>$ 1 GV are shown in dashed lines to emphasize the similarity of the $<$ 1 GV stations, i.e. the small anisotropy. The Irkutsk (6%) and Jungfraujoch (9%) increases are off scale, and the lowest curve is for Magadan.

magnetic loop, e.g. [12]. Although such explanations are possible, the features of GLE 69 were so extreme that we concluded in [1] that they become improbable. These features are (a) the extremely fast rise time of $\sim$ 1600%/min. which is uncharacteristic for CME shock acceleration, (b) the very short duration of $\sim$ 6 min. of P1, which requires explanation why the shock acceleration switches off so abruptly (and then turns on again to produce P2), (c) the abrupt change in spectral index immediately after P1, and (d) the very rapid decrease in anisotropy between P1 and P2. In addition, order of magnitude calculations suggest that the fluence in P1 was too low to produce P2 as a backscattered remnant form beyond 1 AU. On this basis we deduced that the flare and the CME shock were natural candidates to produce P1 and P2 respectively. This was strengthened by the presence of gamma radiation from the decay of pions at the time of P1, which indicates that it was produced low in the corona.

On the basis of the properties of GLE 69 we defined a classical double-pulse GLE as one with a prompt, highly anisotropic first pulse that is seen by only a few NMs within a narrow cone of acceptance, followed by a second, more isotropic pulse seen on many more NMs, but delayed by limited time interval of $\precsim$ 15 min., to ensure that both pulses are caused by acceleration mechanisms associated with the same active region.

A vulnerable aspect of this model is that the flare acceleration of P1 in GLE 69 implies a path length of $\sim$ 1.7 AU in the heliosphere, which is considerably longer

TABLE I

GROUND LEVEL ENHANCEMENTS IN SOLAR CYCLE 23

GLE No	**Date**	**Single or 1st Pulse**			**2nd Pulse (when seen)**			**Incr. rate %/ min; Rise time min.**	**On-set disp min.**	**P_{max} GV**	**Flare**			**CME start/ height**
		Start	**Max**	**%**	**Start**	**Max**	**%**				**Lat. Lon.**	**X-ray imp.**	**X-ray Onset**	
55	1997 1106	12:31 Many	13:28 San2	18 San2				0.4 57	0	Lmks 4.0	S18 W63	X9.4	11:49?	11:39 5.2
56	1998 0502	14:00 Many	14:09 Gsby	10.4 Gsby				2.2 9	0	1.88 Hbrt	S15 W15	X1.1	13:31	13:32 3.3
57	1998 0506	?	?	0						-	S11 W65	X2.7	07:59	07:55 3.8
58	1998 0824	22:42 Sane	22:53 Sane	3 Sane				0.06 11	0	<1 GV	N35 E09	X1.0	21:50	?
59	2000 0714	10:31 Apty	10:42 Thul	83 San2				3.2 9	6	4.0 Lmks	N22 W07	X5.7	10:03	10:25 1.4
60	2001 0415	13:55 Calg	14:11 Pwnk	181 Sopo	14:05 Caps	14:58 Caps	81 Caps	17 16	8	6.69 Aatb	S20 W85	X14.	13:19	13:35 3.3
61	2001 0418	02:36 Tera	03:13 Tera	19 McM	03:23 Sopo	03:35 Sopo	26 Sopo	0.3 37	70	3.66 Irkt	S23 W117	?	00:14?	02:11 5.9
62	2001 1104	16:40 Tera	17:43 San2	5 San2				0.1 57	0	<1 GV	N06 W18	X1.0	16:03	16:13 8.0
63	2001 1226	05:40 Apty	05:55 Apty	12 Sopo				0.3 15	15	1.19 Kerg	N08 W54	M7.1	04:32	05:06 4.2
64	2002 0824	01:24 Kerg	01:37 Kerg	4 Kerg				0.3 13	5	1.7 Yktk	S02 W81	X3.1	00:49	00:59 3.6
65	2003 1028	11:12 Nrlk	11:17 Nrlk	24 Nrlk	11:12 McM	11:53 McM	45 McM	5.5 5	20	4 Lmks	S20 E02	X17	11:00	11:07 3.9
66	2003 1029	21:01 Many	21:15 Sopo	35 Sopo	23:00 Many	24:00 Many	15 Nain	3.3 14	0	6.69 Aatb	S19 W09	X10	20:37	20:43 8.7
67	2003 1102	17:30 Sopo	17:52 Sopo	39 Sopo				2.5 22	10	4.00 Lmks	S18 W59	X8.3	17:18	17:19 3.0
68	2005 0117	?	?	Very Small							N14 W25	X3.8	09:52	09:43 3.2
69	2005 0120	06:49 Sopo	06:54 Sopo	8000 Sopo	06:53 Apty	07:06 Invk	306 Invk	1600 5	10	14.1 Tibet	N14 W61	X7.1	06:39	06:33 4.0
70	2006 1213	02:50 Many	2:57 Mwsn	68 Mwsn	03:07 Thul	03:28 Barb	55 Mwsn	13 7	13	4.61 Jung	S06 W23	X3.4	02:17	02:25 4.2

Aatb=Alma Ata B, Apty=Apatity, Barb=Batrentzburg, Calg=Calgary, Caps=Cape Schmidt, Gsby=Goose Bay, Hbrt=Hobart, Invk=Inuvik, Irkt=Irkutsk, Jung=Junfraujoch, Kerg=Kerguelen, Lmsk=Lomnicki Stit, McM=McMurdo, Mwsn=Mawson, Nrlk=Norilsk, Pwnk=Peawanuk, Sane=Sanae, San2=Sanae NMD, Sopo=South Pole, Thul=Thule, Tera=Terre Adelie, Yktk=Yakutsk.

South Pole and Sanae are not corrected for altitude.

than the $\sim$ 1.2 AU expected from propagation along the Parker spiral. From a detailed timing exercise (but lack of data on the HMF path length), the CDAW in January 2009 could not exclude either the flare or the CME shock as the source of P1.

III. THE GLES OF SOLAR CYCLE 23

This double-source hypothesis was one of the motivations of the CDAW to systematically analyse all the GLEs of SC 23, together with all the electromagnetic signals such as radio, X-ray, and gamma-ray bursts that accompany them. This should greatly facilitate more detailed acceleration and propagation studies. The study is limited to SC 23 partly because these most recent events are by far the best observed ones.

Part of this information is shown in Table I. It excludes radio and γ-ray information. It was compiled from graphical analysis of each GLE, similar to what was done in Figs. 1 and 2. We stress that we included all the available NM data to ensure that no effect was missed. For each event the start time, the time of maximum, and the amplitude is given, together with the NMs on which they were seen. If these features are similar for several NMs, they are listed as ”many”. The column ”onset dispersion” lists the time difference between the earliest and latest onset, because we noted in [1] that there should be a significant difference in onset times if there are multiple pulses. The column P_{max} gives the name of the NM with the highest cutoff rigidity that saw the event. This is a coarse indication of the hardness of the spectrum. The column with increase rate (in %/min.) and rise time (in min.) gives two indicators of the promptness of the event. The most outstanding feature of the table is the prompt nature of GLE 69 (rather than its magnitude - it was second to GLE 05 of 23 February 1956). Its rate of increase, measured on the leading edge of P1, was $\approx$1600 %/min. and rise-time to maximum only $\approx$5 min., while the next two had increase rates rise times of $\approx$17 %/min. and 16 min. (GLE 60), and $\approx$13 %/min. and 7 min. (GLE 70). We have not yet analysed any events before GLE 40 of 25 July 1989 in any detail. However, from several published figures of GLE 05 on 23 February 1956, e.g. [8], it appears that its rate of increase was ”only” $\approx$ 300 %/min. For GLE 69 the peak width at half maximum was only $\approx$ 4 min. while for GLE 05 it was $\approx$ 25 min. Hence, GLE69 seems to be the fastest and narrowest GLE pulse ever

TABLE II
TIME DIFFERENCE (MIN.) BETWEEN GLE ONSET AND ESTIMATED CME LIFT-OFF

GLE	55	56	59	60	61	62	63	64	65	66	67	69	70
ΔT	42	28	9	22	25	23	34	25	5	18	11	16	25

recorded.

Of the 16GLEs in the list, six show a double-pulse nature. However, only three of these, numbers 60, 69, and 70 show the double-pulse feature defined by GLE 69. GLEs 60 and 70 have highly structured first pulses, with several different sub-peaks. GLEs 61 and 66 do not qualify for classical double-pulses because the onset times of the two pulses differ by one and two hours respectively, which suggests that the two pulses were not from a flare and a CME associated with each other. GLE 65 is also excluded because Norilsk was the only station to record the first pulse, and the fact that its associated active region was at 2°E raises questions about whether this could have been an increase along a well-connected field line.

The flare and CME information was supplied as part of the CDAW. All times are Earth observation time. The flare information reveals the well-known association with western flares, which should be well-connected via the HMF, with only three exceptions (58, 61, 65) that fall outside the range 0°W - 90°W. However, a finer association of flare position with GLE magnitude is difficult. The same is true for the association with flare magnitude in terms of X-ray importance; there were five flares that were stronger than the one of 20 January 2005. We note, however, that of the four largest events in Table I, the three west of 23°W (60, 69, 70) exhibit double peak structures while GLE 59 was associated with a flare at 1°W does not. This supports the result in [1] that a double-peak structure is observed for the majority of large GLE associated with solar activity to the west of 25°W. At the very least, GLE magnitude should be a combined function of activity level and the degree of magnetic connectedness between the source and Earth, and the latter is generally unknown in detail.

The quoted CME start times in the last column of the table are the probable ”lift off” times from the sun, calculated from the observed CME speed from the first observation by the LASCO coronagraph. The height, in solar radii, when the CME was first seen is given as the second number. For typical numbers of CME speed of 2000 km/s and the first point of observation at 4 solar radii, this correction from first observation time to lift-off time amounts to $\sim$25 min., and this introduces a significant timing uncertainty.

Table II lists the time difference between this estimated time of CME lift-off and the time of earliest onset of each of the GLEs (3rd column, Table I). One of the central issues to differentiate between CME and flare (or other) acceleration is whether there is sufficient time for the CME to form, to develop a bow shock, and to accelerate particles into a power law up to a few GeV. For first-order Fermi (or shock) acceleration, this acceleration time scale is κ/V^2, where κ is the diffusion coefficient, and V the solar wind speed. On this basis it appears that this time scale should be in the order of several minutes, and hence the available times in Table II become uncomfortably short for CME acceleration. We note, however, that this time scale may be significantly decreased through self-excitation of waves, as was recently calculated by [10].

For the case of GLE 69 the CDAW concluded that, given these uncertainties, a CME shock acceleration source for P1 could not yet be excluded on the basis of timing. This timing forms a central part of the future analysis.

IV. SUMMARY

The complete list of 16 GLEs observed during SC 23 reveals that three of these events, numbers 60, 69, and 70 had the well-defined double-pulse feature of GLE 69 of 20 January 2005, described in [1]. These three were associated with western flares, and hence should have been well-connected. P1 of GLE 69 has by far the fastest rise-time and shortest duration on the list, even when it is compared to the largest GLE of 23 February 1956. More detailed associations between GLE magnitude and flare position, importance, and CME dynamics are not straightforward, and we are presently studying each individual event in detail.

V. ACKNOWLEDGMENTS

We acknowledge the use of data of over 50 NMs, conveniently available in a centralized data base. We are greatly indebted to M.A. Shea and D.F. Smart who established this data base of GLE reports over many years, to M.L. Duldig who took it over form them, and to E.A. Eroshenko who currently maintains it. The flare and CME information was supplied by N. Gopalswamy.

REFERENCES

[1] McCracken, K.G., Moraal, H., Stoker, P.H., J.Geophys. Res. 113, A12101, doi:10.1029/2007JA012829, 2008.
[2] Timashkov, D.A., Yu.V. Balabin, V.V. Borog, et. al., Proc. 30th ICRC, 1, 209, 2007.
[3] Vashenyuk, E.V., G.A. Bazilevskaya, Y.V. Balabin, et. al. Proc. 30th ICRC, 1, 221, 2007.
[4] Bieber, J.W., J.M. Clem, P.A. Evenson, et. al,. Proc. 30th ICRC, 1, 229, 2007.
[5] Grigoryev, V.G., S.A. Starodubtsev, P.A. Krivoshapkin, et. al. Proc. 30th ICRC, 1, 233, 2007.
[6] Balabin,Y.V., B.B. Gvozdevsky, E.V. Vashenyuk, et. al. Proc. 30th ICRC, 1, 257, 2007.
[7] Storini, M., E.G. Cordaro, M. Parisi, Proc. 30th ICRC, 1, 273, 2007.
[8] Vashenyuk, E.V., L.I. Mirsohnichenko, Y.V. Balabin, J. Perez-Peraza, A. Gallegos-Cruz, Proc. 30th ICRC, 1, 257, 2007.
[9] Bieber, J.W., W. Dröge, P.A. Evenson, K.R. Pyle, Ap. J., 567, 622, 2002.
[10] Ng, C.K., and D.V. Reames, Ap. J., 686, L 123, 2008.
[11] Abbasi, R., et al. (IceTop), Ap. J., 659, L65, 2008.
[12] Saiz, A., D. Ruffolo, J.W. Bieber, P. Evenson, R. Pyle., Ap. J., 672, 650, 2008.