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Analysis of the 20 January 2005 cosmic ray ground level enhancement

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Abstract: The SANAE NM observed three distinct intensity peaks during the cosmic-ray ground level enhancement (GLE) of 20 January 2005. Using these observations, together with those of 10 other NMs, it is shown in this paper and the next that there were two distinctly different cosmic ray populations in this GLE, and that these were accelerated in two different regions of the solar corona.

Introduction

GLEs are short-lived, highly anisotropic episodes of cosmic-ray acceleration associated with solar flares [1, 2]. When the flare occurs on the western third of the solar disk, the particles arrive at Earth along the nominal HMF line. Occasionally, e.g. on 4 May 1960, 7 May 1978 and 22 October 1989, the anisotropy in such a western-limb GLE is, however, extreme, and [3] pointed out that this usually happens on only a few of the 30-odd NMs that observe it. They issued a challenge to explain the co-existence of such highly anisotropic, weakly scattered peaks together with longer, stronger scattered increases on the majority of NMs. This challenge has so far gone unanswered.

The GLE of 20 January 2005, one of the largest on record, provides a further example of this phenomenon. We study its highly anisotropic spike-like precursor, together with its more isotropic, subsequent main phase, primarily with the Sanae NM. Other NMs are then used to determine the axes of symmetry of the two increases. In the next paper, [4], we then re-evaluate similar spike-like precursors mentioned by [3], and propose that the properties of both phases of a GLE may require revision of the generic model regarding the acceleration site and propagation to Earth.

Observations

Figure 1 presents observations of the 20 January 2005 GLE by the Sanae 6NM64 neutron monitor (NM) and the 4NMD neutron moderated detector (bare counters) at 71°40'S; 02°51'W, P_c = 0.79 GV. The striking feature is the presence of three pulses, designated as P1, P2, and P3. P1 reached its peak at ~ 06:54:15 and the intensity then fell rapidly to half the peak value in ~2 min. Thereafter, it increased again for the next 8 min., reaching the maximum of P2 at ~07:06. The intensity then declined until 07:16, whereafter it increased once more, reaching a broad peak, P3, at 07:24. It will be shown that this third pulse is due to a swing in the HMF direction during the event, and should thus be considered an integral part of P2.

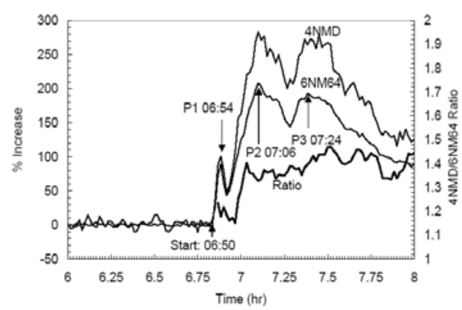

Figure 1: 20 Jan. 2005 GLE as seen on the Sanae 6NM64 and 4NMD, and the 4NMD/6NM64 ratio.

Table 1 and Figure 2 display the observations from several other NMs, with the P1, P2, and P3 times observed at SANAE marked onto the figure. The top part of the table and the dashed lines in the figure are stations that clearly saw P1. The bottom part and the full lines are stations that did not see P1 as a separate pulse. (In the table the South Pole increase is corrected to sea level.)

The six stations that observed P1 clearly all saw the same pulse of radiation, with the first fluxes arriving at 06:49:45±15”. Those that did not see P1 had a spread of starting times that ranged up to 8 min. later. At Mawson, Apatity and Tixie Bay, the starting times are intermediate, probably because P1 was submerged under the larger and later increase of P2. Thule started at the same time as these last stations, but its acceptance cone was so far from the sunward direction of the HMF that it did not even see P2.

Table 1

Station	Start(UT)	P1(UT)	Amp.%	P2(UT)
South Pole	06:49:45	06:53:45	1300	-
McMurdo	06:50:00	06:55:00	2860	-
Climax	06:51:00	06:54:00	542	-
Sanae	06:51:00	06:54:15	90	07:06
Nain	06:51:00	06.56:15	220	07:08
Fort Smith	06:52:45	06:56:15	150	07:05
Mawson	06:51:45	-	-	07:07
Apatity	06:52:45	-	-	07:05
Tixie Bay	06:54:15	-	-	07:06
Inuvik	06.57:00	-	-	07:05
C. Schmidt	06:58:00	-	-	07:07
Thule	06:58:00	-	-	-

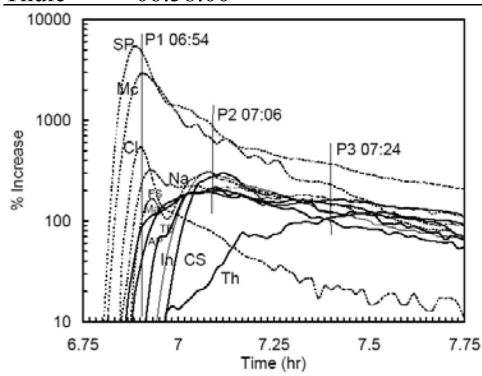

Figure 2: The 20 January 2005 GLE as seen by 10 other NMs.

Figure 3 displays the P1 pulses normalized to the peak intensities. Given the fact that the South Pole increase was ~ 30 times larger than at Sanae, Nain and Fort Smith, there is remarkable agreement between the pulse shape at these stations. The Sanae pulse is, however, more than one min. shorter than those of the others. This key observation will be discussed below.

Thus, the observations indicate that P1 was due to a highly anisotropic, short-lived pulse starting at 06:49:45±15”. As it decreased from its peak, other NMs began to see a slowly increasing pulse starting at ~06:57:30, resulting in P2. The main purpose of this paper and the next, [4], is to show that these two pulses have different origins.

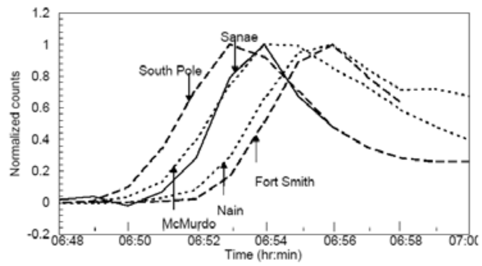

Figure 3: Normalized P1 pulses.

Spectrum

The thick gray line in Figure 1 shows the 4NMD to 6NM64 ratio. Since the former responds to lower energy particles, this indicates that the spectrum gradually softened until ~07:30, whereafter it hardened again to its ambient value. The maximum increases during P2 on the Hermanus (P_c = 4.9 GV) and Potchefstroom (P_c = 7.3 GV) NMs were ~3% and ~1% respectively during P2, indicating that particles were accelerated up to ~ 7 GV. Using the methodology of [5], these observations imply that if the spectrum was a power law in rigidity, it was $P^{-2.7}$ for P1, $P^{-3.9}$ for P2, and $P^{-4.9}$ for P3. Thus, P1 was much harder than P2 and P3, almost as hard as the background galactic cosmic ray spectrum. The softening with time was also observed by [6] and [7]. The latter authors proposed that this was partly due to a harder production spectrum at the start of the event.

Figure 4 shows the asymptotic directions of viewing for these 11 NMs, using the 1995 IGRF. Sanae was the only high-latitude NM that observed all three pulses. It is unique among high-latitude NMs because its acceptance cone is not narrow as is typical for such NMs, but wide as for high cutoff NMs. Thus, Sanae saw (a) the high rigidity (~5 GV) particles coming from ~ 20º S, 15º E, (b) intermediate (2-4 GV) particles from 0º to 20º N and 15 to 35º E, and (c) low rigidity

(< 1.5 GV) particles from > 60º E.

Time Profile of Pulse P1

Figure 3 and Table 1 show that the Sanae counting rate started rising at ~ 06:51 and peaked at ~ 06:54. It then decayed rapidly to 50% of the peak intensity at 06:56. By way of contrast, McMurdo, Fort Smith, and Nain exhibited a broader peak and slower decay; on average they decayed by 50% in 4 to 5 min. These different onset times and peak widths of Sanae and the other four NMs are can be understood in terms of velocity dispersion of a short-lived injection of cosmic rays with a spectrum extending up to ~7 GV. Consider injection onto a field line of length *l,* connected to Earth. As mentioned above, Sanae initially saw rigidities ≥ 5GV with $\beta = v/c \geq 0.96$. Figure 4 shows, however, that the asymptotic cones of the other four NMs that saw P1 are narrow, so they would have seen lower rigidity cosmic rays in the highly anisotropic pulse as well. Particles with speed β and small pitch angles would have taken 8.3 l/β min. to reach Earth. For the Parker field line and a solar wind speed of 400 km/s, l = 1.17 AU, yielding transit times of 10.1 and 15.8 min. for 5 and 1 GV particles respectively. Thus the ~2 min. longer enhancements observed by the other four NMs are consistent with the slower propagation of the low rigidity particles. The short duration of P1 as seen on Climax confirms this, because its cutoff at ~ 2.5 GV is much higher than that of the other NMs in the study. For South Pole and McMurdo, the start time of the event would be due to the higher rigidities as seen by Sanae, while the duration of the peak and its decay rate would be largely determined by the lower rigidities. Figure 4 shows that Fort Smith and Nain would respond preferentially to the lower rigidities in the pulse, leading to their later onset times. Thus, since the first pulse at Sanae was essentially free of velocity dispersion, it provides the most direct information about the near-Sun injection process. This is used in the next paper [4] to determine the nature and the site of this process, as well as that responsible for P2.

Anisotropies

The HMF direction was determined form ACE measurements, 1.4x10^6 km from Earth. After proper delay with the ambient solar wind speed, this yields the effective HMF directions at Earth,

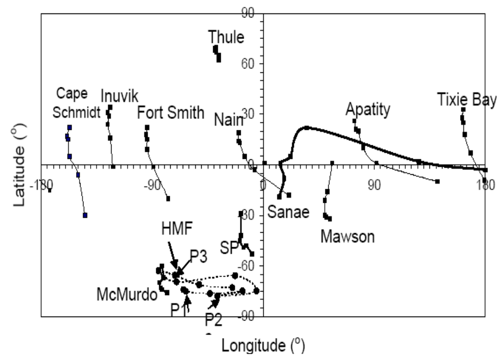

Figure 4: Asymptotic directions for 6, 5, 4, 3, 2, 1 GV particles, with the station name at the 6 GV end. Sanae is shown in bold, and the HMF directions during the GLE in dashed lines.

plotted with dashed lines in Figure 4.

Figure 5 shows the P1 intensities observed by the top 6 stations in Table 1 against the angle between their asymptotic viewing direction and this HMF direction. The e-folding angle of the curve is ~ 45°, indicating highly anisotropic radiation, with almost no radiation coming from for θ >120° (e.g. form Tixie Bay, Cape Schmidt and Inuvik). Although the field swung considerably during the course of the event, it is shown in [8] that the intensity does remain field-aligned, but that the e-folding angle increased to ~ 80° at 07:06 at the peak of P2, to 120° at 07:15, while at 07:30 there was almost no anisotropy left. The nature of P2 was therefore greatly different from P1, exhibiting much slower rise and fall times, and milder anisotropies, similar to more conventional GLEs.

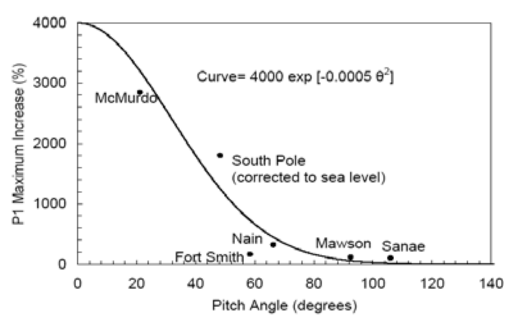

Figure 5: The anisotropy of pulse P1

In the commonly used quasi-linear scattering theory, e.g. [9], the pitch-angle diffusion coefficient is $D_{\mu\mu} = 0.25\pi(1-\mu^2)\Omega^{2-q}v^{-q}\mu^{q-1}B^{-2}$, with μ the cosine of the pitch angle, Ω the gyrofrequency, and with the perpendicular power spectrum $P_\perp$ approximated by $(\Omega/\mu v)^{-q}$, where q is obtained from HMF measurements. This $D_{\mu\mu}$ is plotted in Figure 6 with q = 1.7. This shows that cosmic rays injected near the sun with small pitch angles (due to strong adiabatic focusing, which should be effective as $\propto B \propto r^{-2}$) suffer relatively little scattering. For the same HMF, particles injected further away from the solar surface with larger pitch angles, aided by less adiabatic focusing there, will suffer stronger scattering, leading to a wide range of propagation times, a slow rise time, and milder anisotropy at Earth. That is, the broad characteristics of the P1 and P2 pulses can be explained in terms of the standard QLT, provided the P1 population is injected into the HMF much nearer to the surface of the Sun than P2.

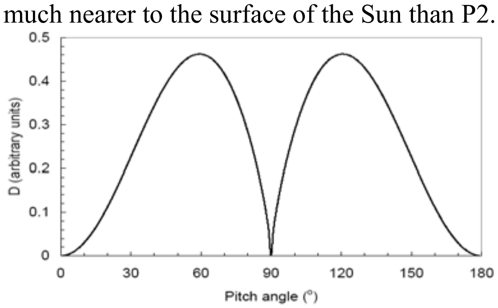

Figure 6: Pitch-angle diffusion coefficient $D_{\mu\mu}$.

From [2] and [3] it follows that the short duration, large anisotropy, and hard spectra of the GLEs of 4 May, 1960 and 7 May, 1978 were similar to P1. This leads us to conclude that all three were produced by similar mechanisms, as discussed in greater detail in [8].

Finally, the intensity at Sanae, and to a lesser extent at Apatity and Mawson, exhibited broad minima in the vicinity of 07:14 , followed by an increasing intensity to P3 at 07:24. The asymptotic cones of all three NMs are in the general direction of 15° N, 80° E. Figure 4 shows that the HMF direction was ~ 65° S, 85° W at 07:14, so the pitch angles reaching the three stations were ~ 130°. Over the subsequent 10 min. the HMF swung to ~ 75° S, 25° W, so that the radiation reaching the three stations was then from pitch angles of ~108°. Thus, the changing HMF direction caused the three stations to progressively sample smaller pitch angles from 07:14 to 07:24, leading to an intensity increase, which provides the natural explanation that P3 is simply a part of the P2 population.

Conclusion

We conclude that the 20 January 2005 GLE is a good representation of GLEs that are due to flares on the western part of the solar disk. In the next paper, [4], we propose that such events commonly consist of (1) a highly anisotropic, short-lived pulse, P1, due to cosmic rays released into the open solar field soon after acceleration, that then travel relatively unscattered to Earth along the Parker field lines; and (2) a slower rising and falling pulse, P2, that exhibits milder field-aligned anisotropies due to stronger scattering, and starts 7-15 min. after P1. In most cases P1 has decayed to $< 50\%$ of its peak before P2 starts.

Acknowledgements

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