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# Variations in cosmic ray intensity observed with the L3+Cosmics shower array detectors and the intense solar flare on 14 July 2000

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**Abstract.**

Intense flare activity on the Sun is known to generate an enhanced flux of particles which are known to be accelerated to energies of at least hundreds of MeV. There is considerable interest in identifying Solar flares with particles accelerated to GeV and higher energies and to study them in detail for better understanding of the acceleration processes occurring on the Sun. An array of 50 unshielded thin scintillation detectors has been operational since April 2000, at the surface above the L3 detector at CERN as part of the L3+Cosmics experiment. Data on the counting rates of these detectors have been examined for possible enhancement in the flux of particles time coincident with the intense Solar flare of 14 July 2000. Details of observations and their implications for the emission of high energy $\sim$ 10 GeV particles during intense Solar flares are discussed.

## 1 Introduction

Observations on variations of cosmic ray intensity at ground level with different types of detectors, such as neutron monitors and muon telescopes, have provided wealth of information on phenomena occurring on the Sun. Intense flare activity leading to large coronal mass ejection and acceleration of particles to high energies have been detected as ground level enhancements (GLEs) in particle flux. Temporal and spectral information on particles associated with GLEs have been of great use in understanding some features of the structure of magnetic fields in the heliosphere. Many attempts have been made to extend the observations to higher and higher particle energies to improve our understanding of the nature of acceleration processes occurring on the Sun during Solar flares. Several observations (Chiba et al., 1992; Alexeenko et al., 1993; Ryan et al., 1999) have shown the presence of particles of energies $\sim$ 10 GeV in GLEs associated with a few of the very intense Solar flares. Some observations (Karpov et al., 1998; Mandzhavidze, 1994) have also yielded interesting but so far inconclusive evidence for a correlation between the observed increase in the flux of particles of energies of several hundred GeV with prominent GLEs. These results highlight the importance of continuous observations on the flux of particles of various energies with different types of detectors at surface as well as underground for improving our understanding of the evolution of high energy processes in the Solar corona and the surrounding medium.

We report here our observations on episodes of increase of rate of counters of the shower array operating above the L3 detector at CERN (Geneva) and possible correlations with particle emission from the Sun, particularly the very intense flare of 14 July 2000. An accompanying paper (Ding, 2001) discusses the results of our search for enhancement in the flux of high energy muons (Le Coultre, 2001) observed with the precision and very large area muon spectrometer of L3. Recent suggestions about association of higher particle flux in the atmosphere with rainfall are also studied.

## 2 Shower Array Detectors

The shower array (Adriani et al., 2001) located on the roof (54m x 30m area) of the hall above the shaft leading to the L3 detector located 30m underground, consists of 50 scintillation detectors, each 100cm x 50cm in area and 10mm thickness. Scintillation photons are collected and guided to the photomultiplier by 1 mm diameter wave-length shifting fibres embedded in 2 mm wide and 2 mm deep sigma-shaped grooves machined on the top surface of the scintillator plates. A part of the anode signal from each detector is amplified (X 10) and discriminated (-30 mV) before being fed to a counter which is read out whenever a shower trigger ($\sim$ 1.6 Hz) is generated. With 2 MeV as the average dE/dx for a near-vertical muon traversing the scintillator, the discriminator threshold has been set at $\sim$ 1 MeV. Therefore, the shower detectors are also sensitive to MeV photons, mainly through Compton scattering. In addition to the recording of air showers (Wilkens, 2001), the counting rate of all the detectors has been monitored over time scales of seconds almost continuously since April 2000.

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## 3 Variation of Detector Rates

The observed rate from any detector consists of three components: (a) signals due to particles and gamma rays, (b) noise signals induced on the long cables by local electrical environment and (c) intrinsic noise signals within the photomultipliers. While (a) is well-known to depend on atmospheric conditions, particularly, the pressure and temperature profile in the atmosphere, (b) is also dependent on the atmospheric conditions, particularly, air conductivity. On the other hand, (c) is mainly related to temperature around the photomultiplier which is located inside the light-tight aluminium box containing the scintillator plates and the WLS fibres. Though this box is protected against direct sunlight by another thin roof and an air gap, the counting rate does depend on the ambient temperature and the intensity and duration of sunlight. Due to various factors, the temporal behaviour of rates (b) and (c) is quite different from detector to detector and at different times due to their distribution over an extended area. However, it has been observed that more than 30 of the 50 detectors are relatively free ('quiet') from environmental effects (b and c) mentioned above on most of the days. This has been experimentally verified by taking a narrow (100 ns) coincidence between the signals from two photomultipliers looking at the same set of scintillators and monitoring the coincidence rates. This additional feature was incorporated in 12 of the 50 detectors for extending the dynamic range of measurement of particle densities for larger air showers.

The statistical significance of any variation of rate of type (a) can therefore be enhanced by averaging over data from all the 'quiet' detectors over any specific time period. Figure 1 shows the variation of the rate over the 24h period on a typical day (20 April 2000) for a typical 'quiet' detector and the rate averaged over 30 such detectors. Figure 1 also shows the variation of the atmospheric parameters, pressure, temperature and relative humidity on this particular day.

Relatively small and very gradual variation in detector rates is very typical for the observations on most of the days. However, there have been days when the rates increased significantly for a period of several hours. Figure 2 shows one such episode which was observed on 23 April 2000 along with data on the atmospheric parameters. The average rate during 00h-13h (Geneva time) was 168.5 Hz which went up to a peak rate of 182.9 Hz during 18h-19h before coming down to 171.1 Hz after 21h. Overall, the average rate was 179.1 Hz during 13h-20h, representing an increase of 6.3% over the average rate during 00h-13h. It is to be noted that the observed variation can not be accounted for in terms of changes in any one of the atmospheric parameters shown in the figure in a simple manner.

Data on counting rates for shower detectors are available for the full period of 24h on 353 days out of 398 days of observations from 13 April 2000 to 15 May 2001. This database has been searched for episodes of rate increase of the type shown in Figure 2 with the following selection criteria: (a) the duration of the increase in the average rate should exceed one hour, and (b) the average amplitude of the increase should be larger than 5%. This search has yielded 43 episodes whose details are listed in Table 1. It is to be noted that the

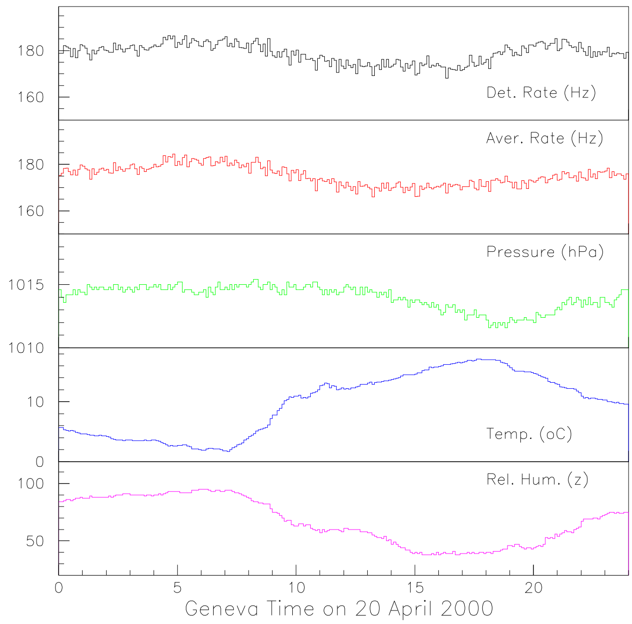


**Fig. 1.** Variation of the rate over the 24h period on a typical day (20 April 2000) for a typical 'quiet' detector and the rate averaged over 30 such detectors. Also shown is the variation of the atmospheric parameters, pressure, temperature and relative humidity.

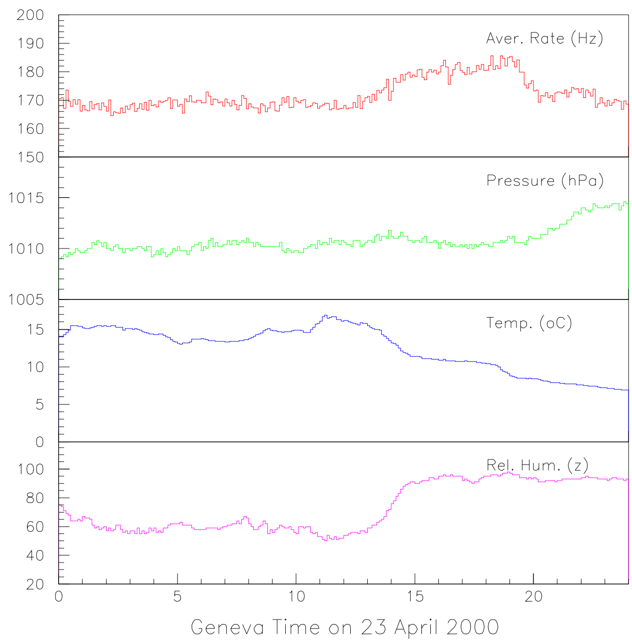


**Fig. 2.** Variation of the average rate over the 24h period on 23 April 2000 along with data on atmospheric pressure, temperature and relative humidity. The enhancement in the rate over the 13h-20h period represents an increase of 6.3% over the quiescent period (00h-13h).

Table 1 : Some Details for the Episodes showing Higher Rate

| Year | Month | Dates of the Rate Episodes | Duration of the Episodes |
|---|---|---|---|
| 2000 | Apr | 23, 29 | 13-20, 05-11 |
| | May | 3, 27, 28 | 18-24, 08-12, 17-21 |
| | Jun | 6, 28 | 01-12, 02-05 |
| | Jul | 4, 10, 12, 14, 28 | 00-08, 08-24, 14-16, 10-15, 02-05 |
| | Aug | 5, 21, 31 | 08-13, 03-05, 00-08 |
| | Sep | 19, 20, 30 | 15-24, 07-19, 01-16 |
| | Oct | 10, 11, 13, 15 | 03-10, 03-16, 07-18, 21-24 |
| | Nov | 3, 6, 23, 25, 26 | 02-11, 02-13, 18-24, 18-24, 06-12 |
| | Dec | 8, 15, 25 | 16-24, 02-06, 00-07 |
| 2001 | Jan | 23, 24, 25 | 00-07, 11-19, 12-18 |
| | Feb | 5 | 01-04 |
| | Mar | 8, 29 | 05-22, 05-14 |
| | Apr | 4, 7, 8, 23 | 16-20, 03-07, 00-12, 06-18 |
| | May | 1, 4, 9, | 13-24, 17-24, 22-24 |

episodes are almost uniformly distributed over the 24h period and the episode duration varies from a few hours to about 12 hours.

Suggestions (Stozhkov et al., 1995; Svensmark, 1998; Marsh and Svensmark, 2000) have been made recently about possible role of higher charged particle flux in the atmosphere in causing enhanced condensation under suitable cloudy conditions. An indication of such a correlation is given by the onset of $\sim$ 100% humidity with the start of the episode on 23 April 2000 (Fig. 2). It is observed that the rate increase seems to act only as a trigger for heavy rainfall and the duration of the rainfall thereafter depends only on cloud parameters. Several episodes have shown coincidence between rate increase, rise of humidity, heavy rainfall and severe thunderstorms. This observation makes some of these episodes quite similar to the event reported by Aglietta et al (Aglietta et al, 1999) based on the rate increase observed for the shower detectors of EASTOP array on 11 July 1996. However, the above interpretation is quite different to the hypothesis of Aglietta et al that heavy rainfall accompanied by severe thunderstorm was the cause of the observed rate increase. It is essential to identify the nature of particles responsible for the increase in rates for deciding between these two interpretations. Also, since heavy rainfall can occur only when there are suitable cloudy conditions, all observed episodes of rate increase may not be associated with rainfall.

## 4 Search for Correlations with Energetic Solar Flares

The rate increase observed with the L3+Cosmics shower detectors may be associated with the increase in high energy particle flux from the Sun. Using data from the proton detectors aboard the GOES-8 satellite, we have searched for possible correlation between the observed episodes of rate increase listed in Table 1 and energetic Solar flares.

Most of the Solar flares observed during our observation period have been relatively small with increase in the flux of 100 MeV protons of only about one or two orders of magnitudes. These flares have not been detected as ground level enhancements (GLEs) by the world-wide network of neutron monitors. However, two Solar flares, on 14 July 2000 and 15 April 2001, have been extremely energetic with increase in 100 MeV proton flux exceeding 3 orders of magnitude. Both these flares have been observed by several neutron monitors with flux enhancements of up to 60%.

The flare of July 14 2000 showed a sudden increase in the X-ray flux at $\sim$ 12h (Geneva summer time, UT+2h) followed by an onset of an increase in the flux of 100 MeV protons at $\sim$ 12h30m reaching the maximum only at $\sim$ 14h. On the other hand, the flux of lower energy (10 MeV) protons had increased by an order of magnitude more than a day earlier and reached its maximum a few hours after the maximum for 100 MeV protons. The neutron monitor at Apatity recorded the maximum flux at 12h40m.

We have compared the time profile of the 100 MeV proton flux and the rate of the Apatity neutron monitor with the time profile of the average rate of shower detectors observed on 14 July 2000 in Figure 3. It is interesting that there was an increase in the average rate on this day during the period 10h-15h (Geneva time, UT+2h) and that the rate reached its maximum value at about the same time as the 100 MeV flux and the rate of Apatity neutron monitor. Averaged over the 5h period (10h-15h), the excess rate (139.8 Hz) represent an increase of 9% over the average rate of 128.3 Hz during 00h-05h and 128.2 Hz during the 15h-24h period.

The observed signals in the shower detectors during the rate increase may have been produced either by an increase in the muon flux or a large increase in the flux of $\sim$ MeV gamma rays or a combination of the two. Due to the requirement of relatively small energy loss in the shower detectors, it is not possible to identify the particle type responsible for the observed increase in the rate. Simple simulations show that the average energy of primary protons/neutrons at the top of the atmosphere would be about 10 GeV to create a flux of muons for detection by shower detectors, assuming the energy spectrum of these protons to be quite steep ($f(E)dE \sim E^{-5}$), as expected for the Solar proton flux.

It is also relevant to mention here that the rate of the L3+C shower trigger, which requires a 3-fold coincidence between detectors in adjacent rows and which has been estimated to be generated only by primary protons of energy $> 10$ TeV, has not shown any unexpected variation during any of the episodes listed in Table 1, including the one observed on 14 July 2000.

The close time-coincidence observed by us between the period of highest rates of shower detectors with the intense Solar flare of 14 July 2000 is very similar to correlations observed earlier in several experiments, e.g., Baksan carpet array detectors with the Solar flare of 29 September 1989 (Alexeenko et al 1993), AGASA shower detectors with the Solar flare of 4 June 1991 (Chiba et al 1992) and MILAGRITO detectors with the Solar flare of 6 November 1997. All these

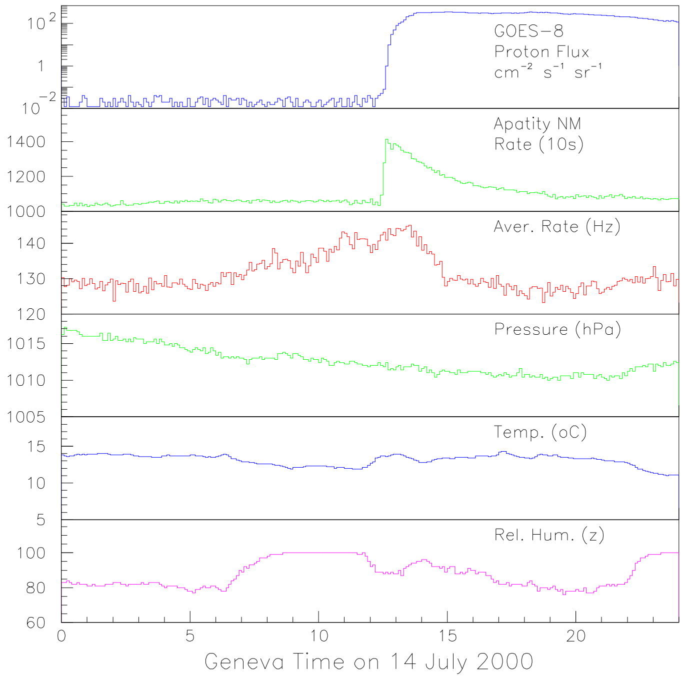


**Fig. 3.** A comparison of the time profile of the 100 MeV flux of protons observed with detectors aboard the GOES-8 satellite and the rate of Apatity neutron monitor with the average rate of shower detectors during the 24h period on 14 July 2000. The average rate of 143.3 Hz during the peak period, 12h30m-13h30m, is 11.7% higher than the rate observed before or after the burst. Figure also shows the variation of atmospheric parameters over the day.

observations together suggest that large flux of protons may be accelerated to energies $\sim$ 10 GeV or even higher in intense Solar flares.

It is interesting to note that heavy rainfall was time coincident with the onset of the increase in cosmic ray particle flux on 14 July 2000 also as suggested by the data on humidity shown in figure 3.

There was no significant increase in the rate of shower detectors on 15 April 2001 at the time of the 2nd large Solar flare of our observation period. However, this is not very surprising as the zenith angle of the Sun was $> 60^o$ at the time ($\sim$ 16h Geneva time) of the flare requiring much higher energy for the protons to produce detectable flux of particles at the altitude of Geneva. Though the Apatity neutron monitor recorded the GLE associated with this flare, the monitors at Mt. Aragats with higher rigidity cut-off did not detect any significant increase in the neutron flux.

Though the other episdes are not directly correlated with specific Solar flares detected as GLEs by neutron monitors, they may also be related to variation in the flux of Solar cosmic rays. Dorman (Dorman, 1976) has suggested that there may be significant changes in the local geomagnetic rigidity cut-off values due to interaction with the Solar wind over time periods of hours. Such changes may allow large flux of Solar protons of energy slightly lower than the nominal cut-off value to penetrate through and cause local increase in the cosmic ray intensity, particularly due to the very steep energy spectrum of Solar protons.

## 5 Summary

We have observed 43 episodes of significant increase in rate of shower detectors during 353 days of observation. The episode on 14 July 2000 was found to be nearly time coincident with one of the most energetic Solar flares of the present (23rd) Solar cycle possibly suggesting acceleration of protons to energy $\sim$ 10 GeV or higher. The other episodes of varying duration and amplitude and occurring at all times of day and night may also have been caused by interaction of Solar particle flux with the geomagnetic field. More detailed studies are required along with more detailed information on the magnetic environment in the neighbourhood of the Earth to understand the phenomenon.

Several of these episodes have been observed to be time coincident with heavy rainfall and thunderstorms which may have been facilitated by the higher density of ionised nuclei in the atmosphere. More studies are required with more detailed information on atmospheric parameters, profile of temperature and cloud density, etc. before firm conclusions can be drawn.

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