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Search for possible enhancement in the flux of high energy muons due to the solar flare of 14 July 2000 with the L3+Cosmics Muon Spectrometer

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Abstract. Several experiments have reported observations on possible correlations between the flux of high energy muons and intense solar flares. If confirmed, these observations would have significant implications for the acceleration processes in the heliosphere so as to be able to accelerate protons and other particles to energies of at least tens of GeV. The solar flare of 14 July 2000 offers a unique opportunity for the L3+Cosmics experiment to search for a correlated enhancement in the flux of high energy muons using the L3 precision muon spectrometer, as the flare occurred when the Sun was almost overhead at Geneva. The L3+Cosmics experimental system and its capabilities for observing a directional excess in the flux of high energy muons are presented here along with observations on 14 July 2000 for two energy regions.

1 Introduction

Since the first observation of solar protons on the ground (so called 'ground level enhancement', GLE) in 1946 (Forbush, 1946) more than fifty GLEs have been detected (Sha and Smart, 1999), mainly using the worldwide neutron monitors (NMs). It has been known that these relatively rare events are related to big solar flares (SFs) and sometimes to strong coronal mass ejection (CME) events, i.e. with highest energy solar processes, and it has been recognised that the Sun can accelerate protons beyond 1 GeV (Park, 1957). However, the details of the particle acceleration is less known. For example, the energy upper limit of solar protons, an important parameter relating acceleration mechanism and environmental conditions of the solar atmosphere, is as yet unknown. From NM observations, evidence for solar protons with energies greater than 10 GeV is still marginal. In recent years several observations using detectors other than NM reported results of solar protons from tens to hundreds of GeV (Chiba, 1992; Karpov, 1997; Lovell, 1998; Ryan, 1999), but these results still need further confirmation. Therefore observations on higher energy particles in GLEs are important.

In recent years the unified analyses of some GLEs with data from different NMs showed (Danilova, 1999; Duldig, 1999; Karpov, 1997; Chebakova, 1999) that solar protons approaching the earth are always anisotropic, coming from an 'asymptotic cone' (Tsyganenko, 1989) with somewhat different peak-time at different NM locations. Therefore, possibly existing higher energy solar protons with lower flux, which can not be detected by NMs, might be detectable by directional detectors, and may appear at some time after the solar flare. This is what motivates us to search for possible signals from the GLE of 14 July 2000 in the L3+Cosmics muon data sample.

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2 The GLE of 14 July, 2000

Since the first monitoring of the solar activity by counting the number of sunspots its 23rd cycle started in June 1996. The year 2000 corresponds to the peak of solar activity of this cycle. On 14 July at 10:24 UT a X5.7/3B class solar flare was produced in the 9077 sunspot region (web1, 2000). Observed by the instrument on board of the Solar and Heliospheric Observatory SOHO/LASCO a full halo, earth directed CME was developping during this event (web1, 2000). Soon after the flare the satellite borne detector GOES-8 observed a rapid increase of proton fluxes with energies larger than 10 MeV, 50 MeV and 100 MeV, respectively (web2, 2000). More than 15 NMs observed cosmic ray intensity increases ranging from 6% to 60% (Usoskin, 2000; Flüeckiger, 2001). Among these, the one having highest geomagnetic rigidity is the Climax NM in Colorado (3 GV), indicating that a solar proton flux up to of 3 GeV was produced. In this note we shall study whether there are solar protons also being accelerated to higher energies in this event.

3 The L3+Cosmics Experiment (L3+C)

The L3+Cosmics (L3+C) detector system (Adriani, 2001) combines the high precision muon drift chambers of the L3 spectrometer at LEP, CERN with an air shower array on the surface. Pictures of the whole system can be seen in contributions to this conference (Le Coultre, 2001 and H.Wilkens, 2001). The L3 spectrometer, located near Geneva (6.02°E, 46.25°N) at an altitude of 450 m, is underneath 30 m of molasse (15 GeV muon cutoff) and installed in a 1000 m^3 magnetic field of 0.5 T. The vertical geomagnetic rigidity cutoff of the experimental site is ∼5 GV. To independently run L3+C without impact on the normal L3 experiment, a "t_0" detector composed of 202 m^2 of plastic scintillators above the muon chamber, and an independent trigger and DAQ electronics were set up. The maximum geometrical acceptance is ∼200 m^2sr and covers zenith angles ranging from 0° to ∼60°. The air shower array, aiming at making coincident observation of air showers and underground muons, is composed of 50 scintillators of size 0.5 m^2, distributed over an area of 30 × 54 m^2. While air shower events are triggered by coincident signals in detectors of three adjacent rows with at least one detector fired in each row, also the counting rate for each single detector is continuously recorded. This permits a summing of the counting rate over any desirable time interval.

Dedicated muon-data taking started in 1999 with a rate of about 450 Hz. Up to November 2000, nearly 12 billion muon events have been recorded within an effective live time of 312 days. Data taking of the air shower array started from April 2000. Nearly 33 million shower events were collected during the year 2000 with about one third associated with the muon trigger.

4 Data analysis

Two data sets of L3+C corresponding to different energy regions were used to search for possible signals from protons produced in the solar flare. One is represented by the high energy muon events detected underground with the L3 spectrometer, and corresponds to higher energy primaries. The second uses the rate of the single detector signals of the air shower array that corresponds to lower energy primaries and will be reported in a separate contribution (Tonwar, 2001).

4.1 Event selection

For the present analysis only well reconstructed muons have been selected. The selection criteria are the following:

1. Only a single muon track is present in the muon chamber;

2. At least a section of the track is composed by 3 segments of hits in P-chambers (wires parallel to the magnetic field) and 2 segments of Z-chambers (wires perpendicular to the magnetic field);

3. The backward tracking of the track from muon chambers to the surface is successful;

4. An additional energy cut is applied for different cases (see below).

4.2 Results from the data sample with E$\mu \geq$ 20 GeV

Muons with energies higher than 20 GeV come from all possible directions of the L3+C acceptance. We select all muons that satisfy the selection criteria and have energies higher than 20 GeV in the L3+C data sample of 14 July 2000. For the minimum muon energy of 20 GeV, if one found signals of solar protons, the most sensitive energy region would be at 50-100 GeV, assuming a E^{-5} solar proton spectrum.

In this analysis the directional cosine

$$l = \sin\theta\cos\phi$$
$$m = \sin\theta\sin\phi$$

are used as measurables of muon directions, where θ and ϕ are zenith and azimuth of the direction of a muon on the surface, respectively. An overall searching procedure was performed for different time windows of 5, 8, 10 and 15 minutes. For the whole angular acceptance and for all data of 14 July, no significant increase in any time window was seen. In order to seek whether some increase came from a particular direction the whole L3+C angular acceptance was divided into 70 smaller bins according to l and m and a 10-minute time window was used. Analyses were done separately for positive muons, negative muons and all muons. With this search, a 3.0 σ excess was found for positive muons in 10 minutes following 14:41 UT and in the sky cell

$$-0.3625 \leq l \leq -0.1625,$$
$$-0.2375 \leq m \leq -0.0375$$

that is, in the south-west direction (at that time the Sun was at $l \sim$ -0.21 and $m \sim$ -0.66). In evaluating the significance, the average rate of the whole day data in the same direction-window was used to estimate the background. However, taking the number of trials (about 10^4) into account, the result is well within the statistical fluctuation.

4.3 The rate of muons in the access shaft direction of L3+C

As mentioned in the last paragraph, no solar protons with energies of 50-100 GeV were seen by L3+C in the solar event of 14 July. Are there lower energy solar protons that can be observed by L3+C? Though most muons entering the L3+C detector have surface energies higher than 15 GeV, lower energy muons can reach L3+C from the access shaft in the south-east direction that can be described approximately by

$$-0.6 \leq l \leq -0.2,$$
$$0.1 \leq m \leq 0.5.$$

It is noted that the Sun was exactly in the shaft direction at the time of the flare. We therefore selected also muons from this window with energies lower than 20 GeV and satisfying the event selection criteria. Taking 8 minutes as a time bin it is found that at 11:15 UT there was a 2.5 σ increase. The background has been estimated by muons from the same direction-window but for different time. An interesting thing is that, at about 11:15 UT, several NMs also observed peak-like increases of the cosmic ray intensity.

From L3+C data and simulation of muons passing through the molasse and the detector it is known that the lowest energy for muons coming from the shaft direction is $\sim$7 GeV. A Monte Carlo calculation using Corsika (Knapp, 1998) was carried out, that took primary protons incident along the shaft direction and set the minimum energy for muons at 7 GeV. It shows that, if muons in the shaft direction are produced by solar protons with an assumed spectrum $\sim E^{-5}$, the sensitive energy region is at 20-50 GeV.

5 Summary

From the present results it cannot be concluded that a statistically significant increase of solar protons with energies in the 20-100 GeV region has been observed by L3+C during the solar event of the 14 July 2000. The L3+C data processing is still going on. We expect final results from a larger data sample.

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