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The X12/3B solar flare that occurred at heliographic coordinates N31, W17 in NOAA region 6659 on 11 June 1991 commencing at 0156 UT was the source of a number of energetic phenomena including intense X-ray and gamma ray emission and the acceleration of ions to relativistic energies. The small associated ground-level enhancement (GLE) of about 6 hours duration was mildly anisotropic even though a geomagnetic storm was in progress. The relative increases at sea level atmospheric pressure ranged between ~3% and ~7% at high latitude neutron monitors. The largest increases were observed by neutron monitors with an asymptotic cone of acceptance viewing into the probable IMF direction. We find a differential rigidity spectrum with a slope of -5.5 provides a satisfactory fit to the observed neutron monitor increases at the GLE maximum.

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THE RELATIVISTIC SOLAR PROTON EVENT OF 11 JUNE 1991

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ABSTRACT

The X12/3B solar flare that occurred at heliographic coordinates N31, W17 in NOAA region 6659 on 11 June 1991 commencing at 0156 UT was the source of a number of energetic phenomena including intense X-ray and gamma ray emission and the acceleration of ions to relativistic energies. The small associated ground-level enhancement (GLE) of about 6 hours duration was mildly anisotropic even though a geomagnetic storm was in progress. The relative increases at sea level atmospheric pressure ranged between ~3% and ~7% at high latitude neutron monitors. The largest increases were observed by neutron monitors with an asymptotic cone of acceptance viewing into the probable IMF direction. We find a differential rigidity spectrum with a slope of -5.5 provides a satisfactory fit to the observed neutron monitor increases at the GLE maximum.

1. INTRODUCTION

The energy source for the 11 June 1991 solar cosmic ray ground-level enhancement (GLE) was the X12/3B solar flare at heliographic coordinates N31, W17 in NOAA region 6659. The H-alpha onset was 0156 UT.

June 1991 was the month of an historic cosmic ray intensity minimum, and this time period was very disturbed with the occurrence of numerous powerful solar flares accompanied by multiple interplanetary shocks propagating through the heliosphere. Five sudden commencement geomagnetic storm onsets were recorded at the earth between 4 and 10 June. The historic cosmic ray intensity low occurred on 13 June 1991. These effects indicate that propagation conditions in the heliosphere were not quiescent.

The world-wide network of neutron monitors recorded a small, mildly anisotropic GLE on 11 June. At the time of the GLE maximum at about 0330 UT stations viewing in the probable "forward" direction such as Apatity, Russia and Mawson, Antarctica recorded an ~7 percent increase while stations viewing in the probable "reverse" direction such as Tixie Bay, Russia and Inuvik, Canada observed an ~3 percent increase as illustrated in Figure 1.

Figure 2 illustrates the onset for some of the "forward viewing" and "reverse viewing" neutron monitors. Unambiguous onset times are difficult to determine because of the small increase recorded. Onsets at the "reverse viewing" stations are later than the "forward viewing" stations. There does not appear to be a definite increase at Tixie Bay until after 0300 UT. The earliest onset for "forward viewing" stations was in the interval 0235-0240 UT.

From the analysis of the asymptotic cones of acceptance of high latitude neutron monitors, we can estimate the flux arriving at both the "forward" and "reverse" viewing stations. Figure 3 illustrates the asymptotic directions for selected high latitude neutron monitors and their orientation with respect to the sun-earth line.

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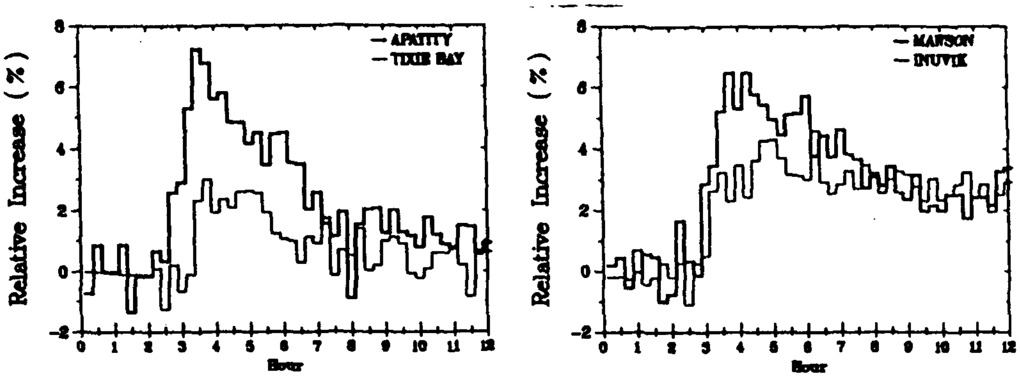

Figure 1. The 11 June 1991 GLE as observed by selected high latitude neutron monitors. Left: Apatity, Russia (forward viewing) and Tixie Bay, Russia (reverse viewing). Right: Mawson, Antarctica (forward viewing) and Inuvik, Canada (reverse viewing).

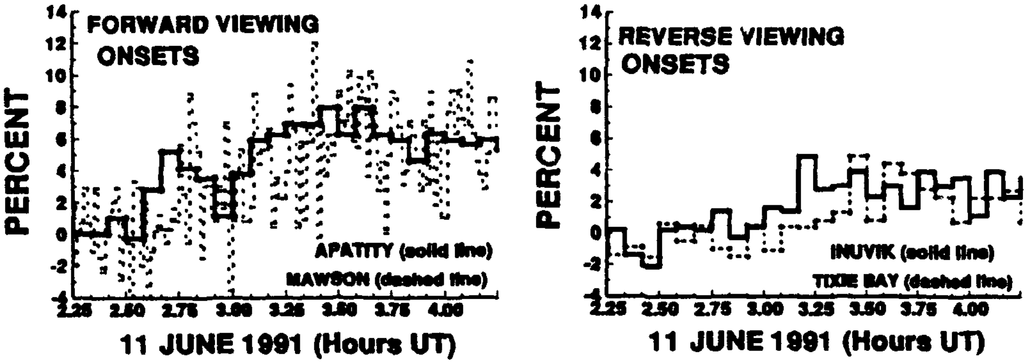

Figure 2. Onset times of the 11 June 1991 GLE. Left: "forward viewing" stations. Right: "Reverse viewing" stations.

Unfortunately, there are no interplanetary magnetic field (IMF) measurements for 11 June 1991. However, we are confident that the solar protons propagated along the direction of the interplanetary magnetic field, and we can use the anisotropy of the observed increases and the onset times to approximate the probable IMF direction to at least the proper octant.

At the time of the GLE the geomagnetic field was severely disturbed, and a geomagnetic storm was in progress. At the GLE onset the Dst was -96 nT and increasing toward the maximum of -140 nT which was observed at 06 hours UT. In our analysis of this event, the IMF direction does not appear to be stable during the GLE, but in our opinion, this is not a serious impediment to making a useful spectral determination since this event is only mildly anisotropic.

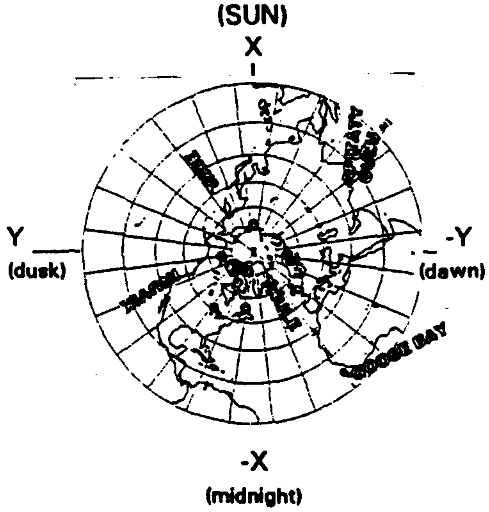

Figure 3. The orientation of the asymptotic directions of approach for selected neutron monitors. At the GLE maximum (0330 UT), the sub-solar point was at 23° N latitude, 127° E longitude.

2. THE RELATIVISTIC SOLAR PROTON SPECTRA DETERMINED FROM THE ANALYSIS OF NEUTRON MONITOR DATA

We have used our standard technique for the analysis of GLEs (Shea and Smart, 1982) to determine the spectral characteristics and flux anisotropy of the 11 June event. The method is designed to reproduce the increase observed by the individual neutron monitors around the world. This is done from a numerical analysis of the solar particle spectrum, the flux anisotropy, the asymptotic cone of acceptance for each station and the neutron monitor yield function (Lockwood et al., 1974). For this analysis we have used the Debrunner et al. (1982) neutron monitor yield functions to successfully reproduce the observed increases at each neutron monitor. We model the increase utilizing the functional form,

$$I = \sum_{P_0}^{\infty} J(\alpha,P)\, S(P)\, G(\alpha)\, dP \qquad (1)$$

where I is the increase at the neutron monitor, P_0 is the cutoff rigidity, $J(\alpha,P)$ is the differential flux in the interplanetary medium at pitch angle α and rigidity P that is allowed through the asymptotic cone of acceptance, S(P) is the neutron monitor specific yield as a function of rigidity, and $G(\alpha)$ is the anisotropic pitch angle distribution.

In describing our method it is necessary to explain the concept of asymptotic directions of approach. Charged particles of a specified energy arriving at a detector in a specific direction can be "mapped" to a specific direction in space (McCracken, 1962; Gall et al., 1982).

The asymptotic direction of approach defines an allowed particle's direction in space prior to its interaction with the earth's magnetic field. In our model calculations we define pitch angle "zero" as the direction of the maximum particle flux which generally corresponds to the direction of the interplanetary magnetic field.

Figure 4 illustrates the pitch angle distribution required to generate the observed particle anisotropy at the GLE maximum. This form is similar to the exponential form derived by Beeck and Wibberenz (1986).

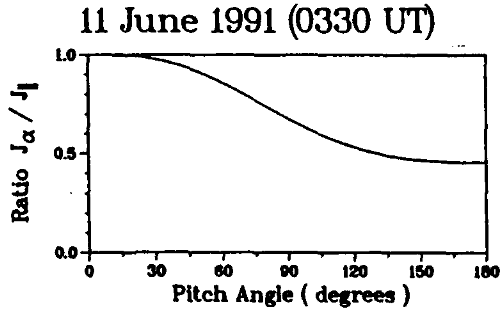

Figure 4. Solar particle flux pitch angle distribution necessary to produce the observed variation in the high energy solar proton flux at high latitude neutron monitors at the 0330 UT maximum of the 11 June 1991 GLE.

A power law in rigidity having a slope of -5.5 yields a satisfactory fit between the increases observed at the various neutron monitors as a function of latitude. For this event there were no significant increases reported for stations where the geomagnetic cutoff exceeded 4 GV. A harder spectrum would generate an increase at stations having a cutoff rigidity > 4 GV.

In our analysis we determine the magnitude of the particle flux parallel to the IMF direction, and the flux averaged over all directions. For this event the differential power law in rigidity that fits the neutron monitor data in the range of 1 to 4 GV is:

$$J_{\parallel} = 4.93\ P^{-5.5}; \quad \text{and} \quad J_{(avg)} = 3.49\ P^{-5.5}. \qquad (2)$$

$J_{||}$ is the flux in units of (cm^2-s-ster-GV)$^{-1}$ parallel to the interplanetary magnetic field (i.e. pitch angle of zero). $J_{(avg)}$ is obtained by averaging the anisotropic flux over 4π steradians.

We can compare the results of this analysis with the solar particle flux observed by earth-orbiting spacecraft at lower energies. In Figure 5 we compare the spectra of the more rigid particles (>1 GV or > 433 MeV) derived from the analysis of neutron monitor data with the GOES-7 five-minute data (H. Sauer, private communication) for the time of the GLE maximum at 0330 UT. In addition to data at 30, 50, 60 and 100 MeV, there is a higher energy particle detector on the GOES-6 spacecraft from which the integral flux above 355, 433 and 505 MeV can be obtained. We have integrated the differential rigidity spectra derived from the analysis of the neutron monitor data and extended it to 30 MeV for comparison. Inspection of this figure shows that the solar particle flux data from ~4 GV (3.17 GeV) to 0.45 GV (100 MeV) fit a simple power law in rigidity with a slope of -5.5. The spacecraft data in the range from 300 to 30 MeV show a velocity dispersive time of maxima between 0430 and 0500 UT. These data (indicated by the • symbol in Figure 5) can be used to construct a time-of-maxima spectrum.

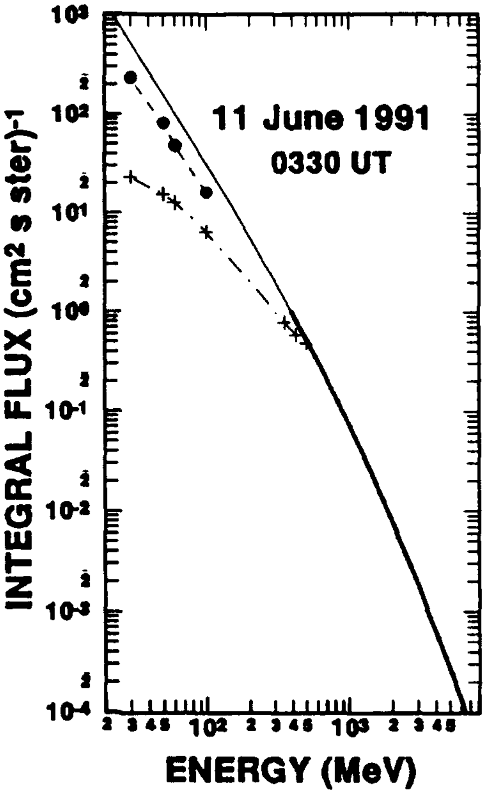

Figure 5. Spectrum derived for the GLE of 11 June 1991 converted to an integral energy spectrum for comparison purposes. The heavy dark line indicates the spectrum derived from analysis of the neutron monitor data. The light line is this spectrum extended to spacecraft measurement energies. The + symbol indicates the spacecraft measured integral flux at 0330 UT. The • symbol indicates the spacecraft measured integral flux during the 0430-0500 UT maximum.

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