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THE RELATIVISTIC SOLAR PROTON GROUND-LEVEL ENHANCEMENTS ASSOCIATED WITH THE SOLAR NEUTRON EVENTS OF 11 JUNE AND 15 JUNE 1991.

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ABSTRACT

The Solar Cosmic Ray Ground-Level Enhancements (GLEs) observed on 11 and 15 June 1991 were distinctly different in character. The small GLE on 11 June was mildly anisotropic with an approximately 2-to-1 ratio in the relativistic proton flux observed by "forward viewing" high latitude neutron monitors as compared with the flux observed by "reverse viewing" high latitude neutron monitors. In contrast the 15 June GLE was almost isotropic in spite of the fact that the source solar flare position was at heliolongitudes that were presumably "well-connected" to the earth via the average interplanetary magnetic field topology. A differential power law in rigidity seems to fit the data in the region between 1 and 6 GV for both events. For the 11 June GLE maximum our derived slope is -5.5. For the 15 June GLE maximum our derived slope is -6. It is our opinion that the lack of observed flux anisotropy during the 15 June GLE is probably due to the very disturbed interplanetary propagation conditions rather than solar source characteristics.

I. INTRODUCTION

The episode of solar activity that occurred during June 1991 generated a number of energetic phenomena including intense X-ray and gamma ray emission, solar neutron emission, and the acceleration of ions to relativistic energies detectable at the earth. The details of these solar flares and their energetic X-ray, gamma ray and solar neutron emission are described elsewhere in this volume and will not be repeated here. The powerful solar flares in this activity episode generated interplanetary shocks that propagated through the heliosphere. Six sudden commencement geomagnetic storm onsets were recorded at the earth between 4 and 12 June. The intense solar activity contributed to the historic cosmic ray intensity minimum observed during this month. While the effects of this activity episode on the propagation conditions in the heliosphere have not been fully ascertained, all of these effects strongly suggest that propagation conditions were not quiescent. Also suggestive of the non-quiescent propagation conditions were the variations in the pre-event cosmic ray background which exceeded the variations expected from Poisson statistics.

The energy source for the solar cosmic ray ground-level enhancements (GLEs) studied in this paper were energetic solar flares in NOAA region 6659. The 11 June 1991 GLE is time-associated with the X12/3B solar flare at heliographic coordinates N31, W17 having an H-alpha onset of 0156 UT. The 15 June 1991 GLE is time-associated with the X12/3B solar flare at heliographic coordinates N33, W69 having an H-alpha onset of 0810 UT. The historic cosmic ray intensity low was recorded on 13 June 1991, in the interval between these two GLEs.

II. METHOD OF DETERMINING HIGH ENERGY SOLAR PARTICLE SPECTRA FROM THE ANALYSIS OF NEUTRON MONITOR DATA

An introduction to the general concept of using cosmic ray neutron monitor data for the analysis of high energy solar proton events is given in this volume by Debrunner[1] and that material will not be repeated in this paper. We have used our standard technique for the analysis of GLEs[2] to determine the spectral characteristics and flux anisotropy of the June GLEs. 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[3]. For this analysis we have used the Debrunner[4] et al. neutron monitor yield functions to reproduce the observed increases at each neutron monitor. We have limited the form of the spectral parameters used to a differential power law in rigidity which seems to produce a satisfactory fit to the neutron monitor data in the rigidity range between 1 and 6 GV.

We model the increase utilizing the functional form,

$$I = \sum_{R_c}^{\infty} J_{\alpha}(\alpha,R)\, S(R)\, G(\alpha)\, \Delta R \qquad (1)$$

where I is the increase at the neutron monitor, R_c is the cutoff rigidity, $J_{\alpha}(\alpha,R)$ is the differential flux in the interplanetary medium at pitch angle α and rigidity R that is allowed through the asymptotic cone of acceptance, S(R) is the neutron monitor specific yield as a function of rigidity, and $G(\alpha)$ is the anisotropic pitch angle distribution. In our modeling approach we sum the spectrum-yield response for each station from 0.7 (or the cutoff rigidity) at 0.1 GV intervals to 25 GV.

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 from a specific direction can be "mapped" through the geomagnetic field to a specific direction in space[5,6,7]. The asymptotic direction of approach defines an allowed particle's direction in space prior to its interaction with the earth's magnetic field. From the "geomagnetic optics" of high latitude neutron monitors, we can determine the orientation of the asymptotic cone of acceptance to the interplanetary magnetic field direction and estimate the flux arriving at each station. 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.

III. THE GLE OF 11 JUNE 1992

The world-wide network of neutron monitors on the earth recorded a small, mildly anisotropic GLE on 11 June. For this event there was an impulsive onset at the forward viewing stations (those having asymptotic directions of approach viewing into the solar particle flux propagating along the interplanetary magnetic field direction away from the sun) in the five-minute interval 0235-0240 UT[8]. The onset for reverse viewing stations (those having asymptotic directions of approach viewing into the particle flux propagating along the interplanetary magnetic field back toward the sun) was after 0300 UT. 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 increase of ~7 percent while stations viewing in the probable reverse direction such as Tixie Bay, Russia and Inuvik, Canada recorded an increase of ~3 percent. An overall conceptual view of this small GLE can be obtained from Figure 1. In this composite figure we show the asymptotic viewing directions for selected high latitude neutron monitors on the right. The top left shows the increase observed by a station viewing into the forward propagating flux and a station viewing into the reverse particle flux. The bottom left illustrates the pitch angle distribution required to generate the observed particle anisotropy at the GLE maximum[8]. This form is similar to the exponential form derived by Beeck and Wibberenz[9] .

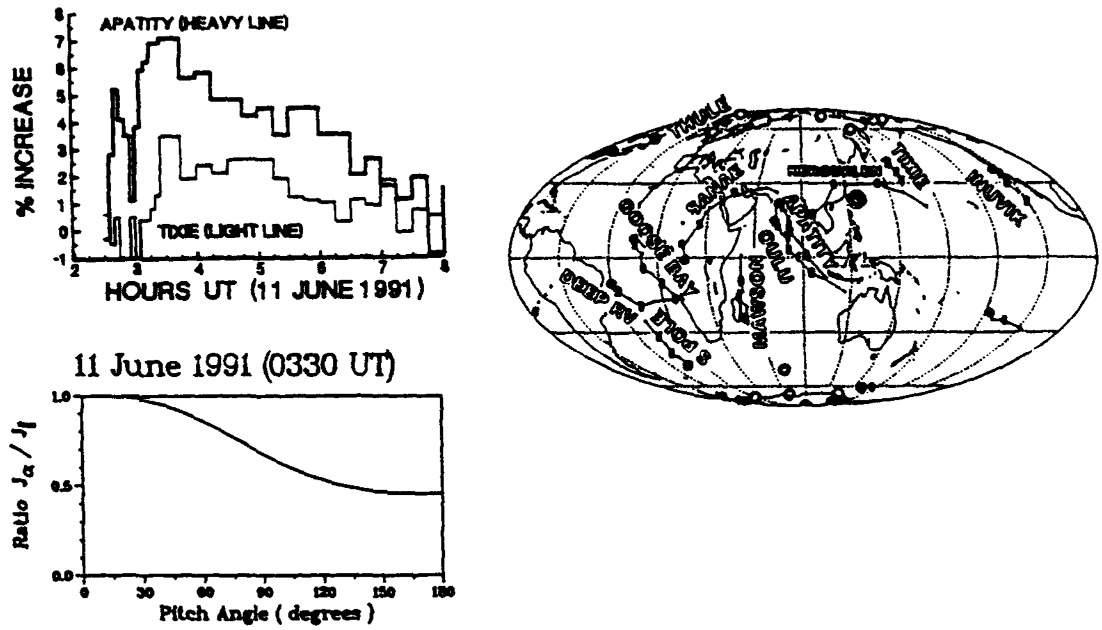

FIG. 1. The 11 June 1991 GLE. Left top: relative increase observed by Apatity, Russia (forward viewing) and Tixie Bay, Russia (reverse viewing). Right: Display of the asymptotic viewing directions responsible for 10 to 90 percent of the response of selected high latitude neutron monitors. (Five minute data are displayed until maximum; 15 minute averages thereafter.) At the time of the GLE maximum (0330 UT), the subsolar point was at 23° N, 127° E. Bottom left: Solar particle flux pitch angle distribution necessary to produce the observed variation in the high latitude neutron monitors at the GLE maximum.

Unfortunately, there are no interplanetary magnetic field (IMF) measurements by earth-orbiting spacecraft for 11 June 1991. However, we can use the anisotropy of the observed increase and the onset time to approximate the probable IMF direction, at least to the proper octant. 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 did not appear to be stable during the GLE, but in our opinion, in this case this is not a serious impediment to making a useful spectral determination.

A power law in rigidity having a slope of -5.5 yielded a satisfactory fit between the increases of the various neutron monitors as a function of latitude. For this event there were no significant increases reported for stations whose geomagnetic cutoff exceeded 4 GV. A harder spectrum would predict increases at stations having a cutoff rigidity > 4 GV. We determined 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 at the 0330 UT GLE maximum is:

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

$J_{\parallel}$ 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 summing the anisotropic flux over 4π steradians.

A. Comparison of the 11 June 1991 GLE Spectra with Spacecraft Data.

We can compare the spectrum of the more rigid particles (> 1 GV or > 433 MeV) derived from the analysis of neutron monitor data with the GOES 6 and 7 five minute data. We have integrated the GLE spectrum derived from the analysis of the neutron monitor data and extended it to 30 MeV as illustrated in Figure 2. The heavy line in this figure indicates the spectrum that is derived from the high energy flux observed by the neutron monitors at the 0330 UT GLE maximum. The light line is an extension of this spectrum to the spacecraft measurement energies. The + symbol identifies the spacecraft observed fluxes at the time of the GLE maximum.

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 integral flux above 355, 433 and 505 MeV can be obtained[10]. We have plotted these data in Figure 2 for comparison. The empirical correction for side penetration of the sensor by high energy particles provided by Sauer[10] has been applied to these data. The spacecraft data show a velocity dispersive time-of-maxima in the initial part of the event. The velocity dispersive flux maximum for energies > 300 MeV to > 30 MeV occurred after the 0330 UT GLE flux maximum, between 0430 and 0500 UT. These data (indicated by the • symbol in Figure 2) can be used to construct a time-of-maximum spectrum.

The GOES spacecraft particle flux data[10] for this event are shown in Figure 3. To our biased observations, there are two maxima displayed in these data. A velocity dispersive flux maximum occurs between 0330 UT and 0500 UT. There is a second, larger and non-velocity-dispersive flux maximum that occurs at about 14 hours UT during an extended period of increased magnetic activity when Dst exceeds -100 nT. It is our opinion that this strongly indicates an interplanetary source of the particles contributing to the second maximum. In view of this we are reluctant to take the integrated fluence observed by earth-orbiting satellites for this event and extrapolate it back to the sun to estimate the number of protons released from the acceleration site.

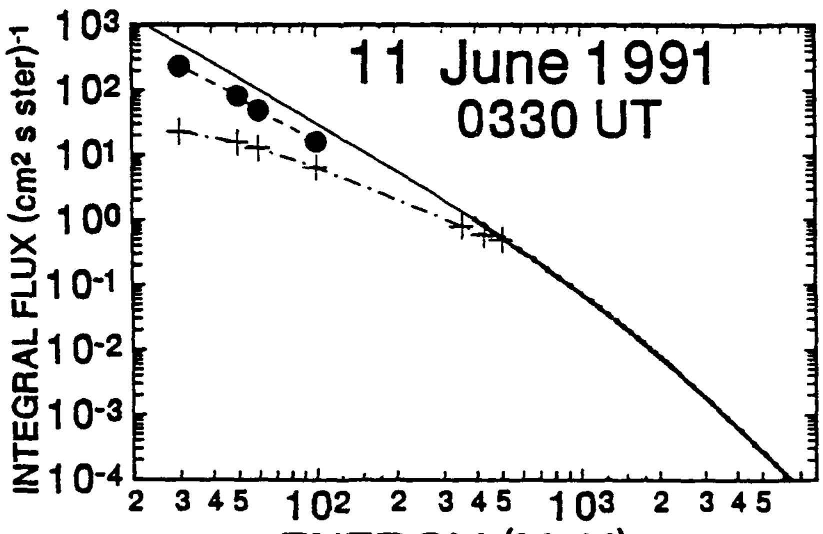

FIG. 2. Integral energy spectra for the GLE of 11 June 1991. The heavy dark line indicates the spectrum derived from neutron monitor data. The light line is the extension to satellite measurement energies. The + symbol indicates the spacecraft measured integral flux at the time of the GLE maximum (0330 UT). The • symbol indicates the spacecraft measured integral flux during the 0430-0500 UT maximum.

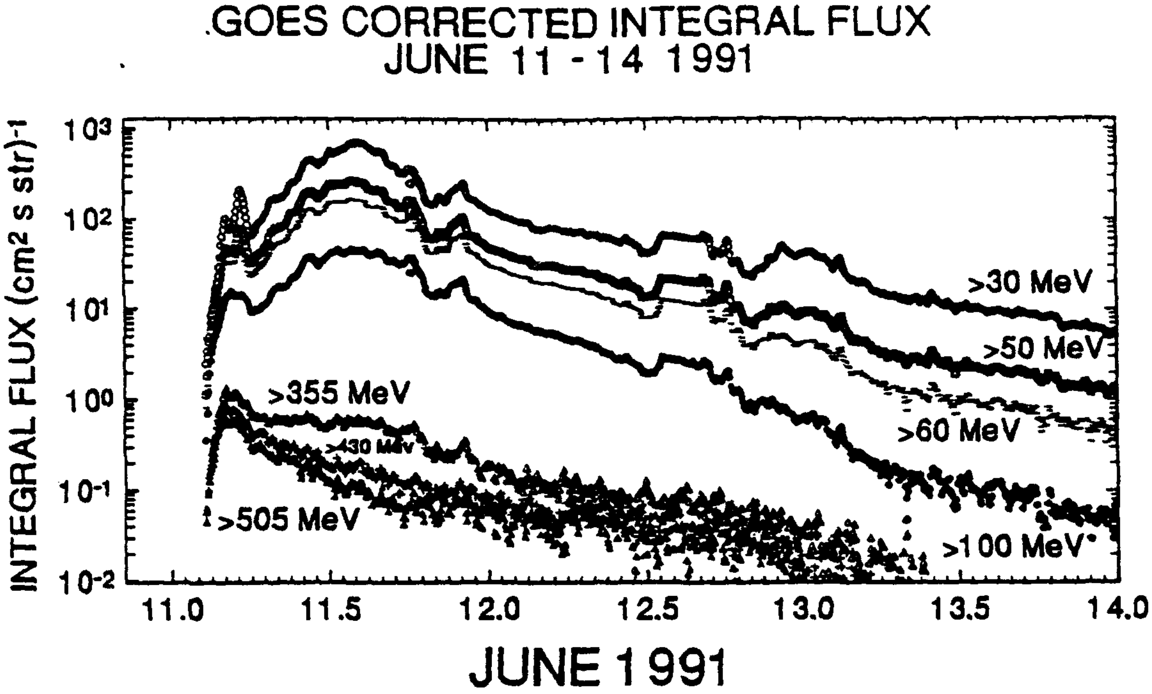

FIG. 3. The solar particle flux observed by the GOES spacecraft for the 11 June 1991 event. Note the non-velocity-dispersive maximum at about 14 hours UT which corresponds in time to the maximum of the geomagnetic storm.

IV. THE GLE OF 15 JUNE 1991

The world-wide network of neutron monitors recorded a small, approximately isotropic, long-duration GLE on 15 June. The disturbed propagation conditions make it difficult to determine precisely the onset of this relatively slow-rising GLE. The increase systematically equaled or exceeded the pre-event background variations in the 0835-0840 UT time interval[12]. All high latitude stations definitely exceeded the pre-event background variations after 0840 UT. We cannot identify a definite anisotropy in the onsets of the forward viewing stations as compared to reverse viewing stations. The IMP-8 spacecraft recorded a velocity-dispersive onset in its measurement range of 8 to 400 MeV[13]. The onset for the highest energy measurement (190-400 MeV) is in the 0835-0840 time interval, essentially in time coincidence with the neutron monitor onsets.

At the time of the GLE maximum at about 0930 UT all high latitude neutron monitors recorded an increase of $\sim 20 \pm 4\%$. There was a very small flux amplitude anisotropy with stations viewing in the forward flux propagation direction such as Goose Bay, Canada recording an ~ 22 percent increase while stations viewing in the reverse flux propagation direction such as Tixie Bay, Russia observed an increase of ~ 17 percent. An overall view of this long lasting, approximately isotropic GLE is presented in Figure 4.

There are direct interplanetary magnetic field (IMF) measurements by earth-orbiting spacecraft for 15 June 1991 until 09 hours UT. Then there is a 4 hour data gap, one hour of IMF data at 14 UT, a one hour data gap, and then IMF data are present for UT hours 16 through 20. Fortunately there did not appear to be large variations in the hourly averaged IMF direction and we assumed that the IMF direction does not have large deviations during the data gaps. At 09 hours UT the observed IMF was at GSE latitude -23°, and GSE longitude 145°. Therefore the probable viewing direction into the solar proton flux was at GSE longitude of -35°.

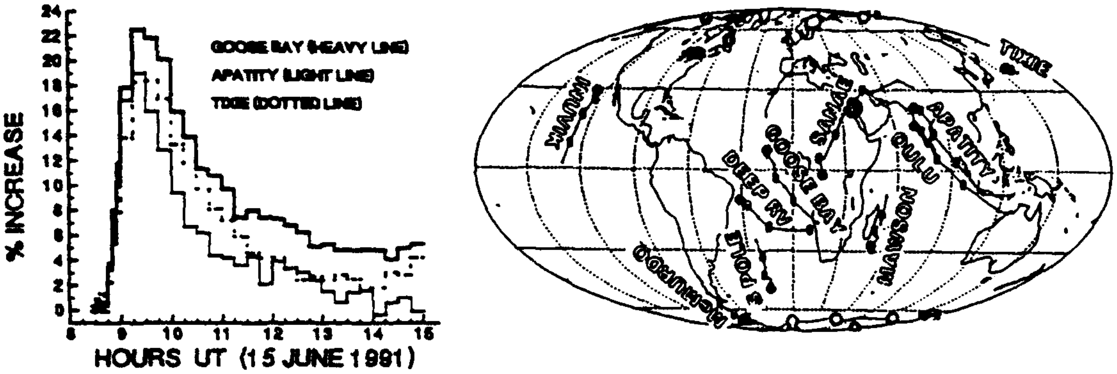

FIG. 4. Illustration of the essentially isotropic GLE of 15 June 1991. Left: Relative increase observed by selected neutron monitors. Right: Display of the asymptotic viewing directions responsible for 10 to 90 percent of the response of selected high latitude neutron monitors. At the GLE maximum (0930 UT), the subsolar point was at 23° N, 37.5° E.

The geomagnetic field had been severely disturbed, and was undergoing a slow recovery from a major geomagnetic storm. At the GLE onset the Dst was -41 nT and was slowly recovering during the remainder of the day.

A power law in rigidity having a slope of -6.0 yields a satisfactory fit to the increases observed by the various neutron monitors as a function of latitude. For this event there were measurable increases for stations at a quiescent geomagnetic cutoff of ~6 GV. In our analysis method, if we assume an omnidirectional flux, a differential power law in rigidity with a slope of -6.0 generates the observed 0.7% increase at Rome (R_c = 6.3 GV) and an equivalent increase when corrected to sea level at the 18-NM-64 neutron monitor (3340 meters altitude) at Alma-Ata, Kazakhstan (R_c = 6.6 GV). When we include the slight anisotropy we find that the spectrum cannot be harder than -5.5 or we would predict a larger increase than was observed at these stations. Since this was a long duration GLE we can also determine the spectrum at other times. We derive a differential rigidity spectrum which gives the flux, J, in units of $(cm^2\text{-}s\text{-}ster\text{-}GV)^{-1}$. We find the high energy solar cosmic ray differential rigidity spectrum to be

$$J = 19.7\,P^{-6.0} \quad \text{at 0930 UT, and} \quad J = 12.5\,P^{-6.0} \quad \text{at 1030 UT.}$$

A. Comparison of the 15 June 1991 GLE Spectra with Spacecraft Data.

In Figure 5 we have integrated the spectrum derived from the analysis of the neutron monitor data and extended this spectrum to the lower energies for comparison with data from the GOES spacecraft. The heavy line in each panel indicates the spectrum derived from the high energy flux observed by the neutron monitors; the left panel shows the spectrum at the 0930 UT GLE maximum, the right panel one hour later. The light line is an extension of this spectrum to the spacecraft measurement energies. The + symbol identifies the spacecraft observed fluxes at each time for energies of >505 MeV, >433 MeV >355 MeV, >100 MeV, >60 MeV, >50 MeV and >30 MeV. The cosmic ray intensity was rapidly recovering from its historic intensity low on 13 June and overwhelmed the remnant of the high energy solar cosmic ray flux after 17 June.

Inspection of this figure shows that the power law in rigidity with a slope of -6.0 does not smoothly extrapolate to the spacecraft energies below 100 MeV. Further inspection of this figure suggests that a "broken power law" type of spectrum may be a better representation of the solar particle flux which evolves extremely slowly for a "well connected" solar particle event.

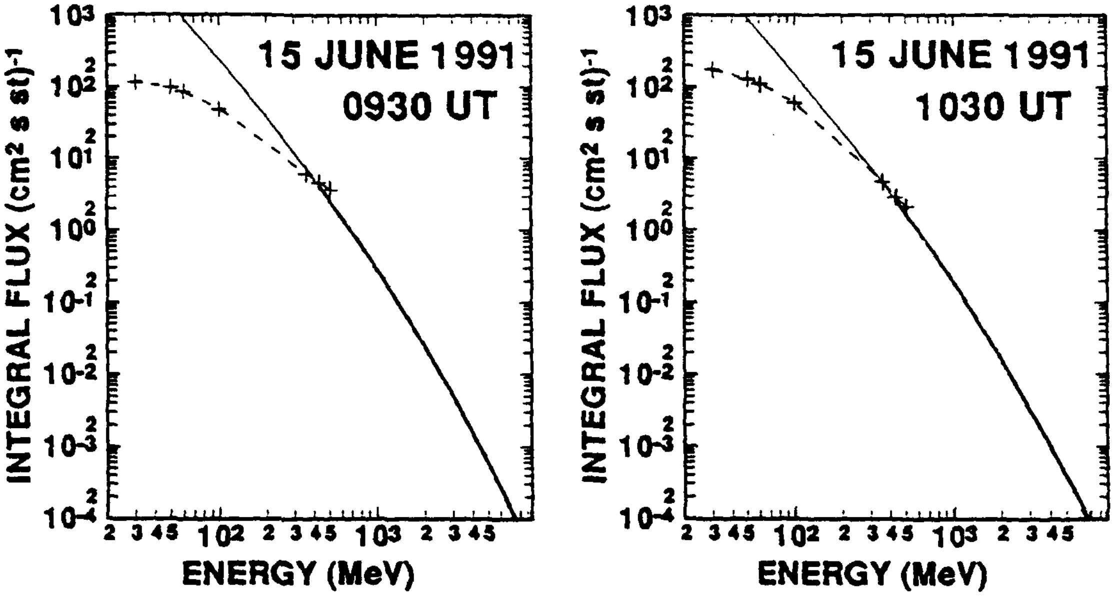

FIG. 5. Spectrum derived for the GLE of 15 June 1991 at 0930 UT (left) and 1030 UT (right). The differential rigidity spectrum has been integrated and converted to an integral energy spectrum for comparison purposes. The heavy dark line indicates the spectrum derived from neutron monitor data. The light line is this spectrum extended to the satellite measurement energies. The + symbol indicates the measured satellite integral flux at each indicated time.

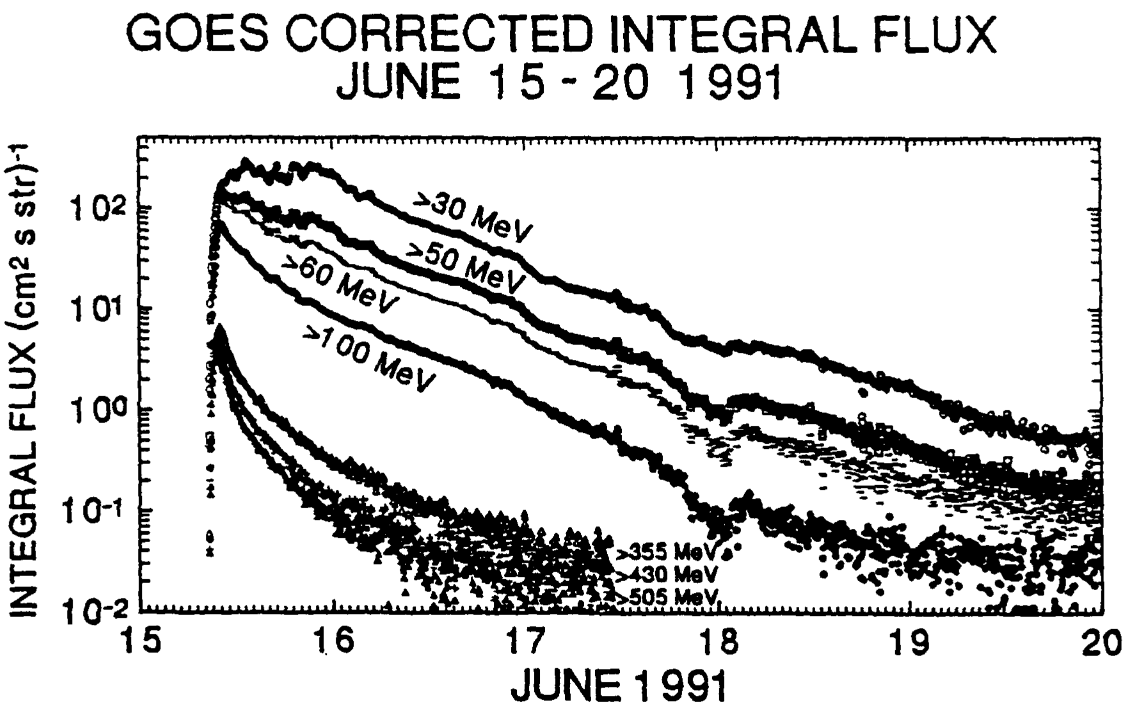

FIG. 6. The solar particle flux observed by the GOES spacecraft for the 15 June 1991 GLE and associated solar proton event. The empirical correction for side penetration of the sensor by high energy particles provided by Sauer[10] has been applied to these data.

The GOES spacecraft particle flux data for this event are shown in Figure 6. In spite of the velocity dispersive onset observed by the IMP-8 spacecraft[13], the flux maximum has only a weak velocity dispersion. The GLE maximum (particles with energies $> \sim 1$ GeV) occurred at about 0930 UT, and the maximum for energies between >50 MeV to >100 MeV occurred at about 1000 UT. It is our opinion that the intensity-time profile indicates that interplanetary diffusion controls both the spectral evolution and the intensity-time profile. Under these circumstances, these observations at 1 AU may not be representative of the particle source release profile.

Acknowledgment

We thank all the principal investigators who have contributed to the GLE data base. This data base is accessible to those who have the capability for remote network connections. Contact Gentile@PLH.AF.MIL, or AFGLSC::Gentile for access instruction. We wish to express special thanks to E. Eroshenko who provided data from the Russian neutron monitor network.

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