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SOLAR COSMIC RAYS, 1960-1989**M.A. Shea****Geophysics Laboratory, Hanscom AFB, Bedford, MA 01731, USA****Abstract**

A synopsis of some of the significant scientific advancements achieved from the analysis of solar cosmic ray events from 1960 through the end of the 21st solar cycle is presented. The unprecedented relativistic solar proton events that occurred in 1989 are discussed in relation to those that occurred during the previous five solar cycles.

Introduction. There have been 32 relativistic solar proton events detected at the earth between 1960 and 1988. Since these ground-level enhancements (GLE) are relatively unusual with only 39 events documented between 1942 and the start of the 22nd solar cycle, most of them have been intensively studied. The events prior to routine satellite measurements are discussed by Simpson (1990). This paper concentrates on the significant scientific advances that have been achieved from the analysis of selected solar cosmic ray events since early 1960 and presents a brief overview of the cosmic ray measurements during the seven ground-level enhancements that occurred in 1989.

Ground-Level Enhancements, 1960-1984. The major events of the 19th solar cycle (1954-1964) presented scientists with an unique opportunity of recording and analyzing these increases using data acquired by the world-wide network of standardized neutron monitors (Simpson, 1957) initially established for the International Geophysical Year. The first significant relativistic solar particle enhancement since the major event in February 1956 occurred on 4 May 1960. This event, associated with a flare at 90° W, generated increases of over 250% at North American high latitude neutron monitors while increases of only a few percent were recorded by comparable detectors in Europe. This extreme anisotropy demonstrated the role of the interplanetary magnetic field in the propagation of solar particles. In addition, the relatively short duration of this event demonstrated the fast transport of these particles well beyond the orbit of the earth.

A major sequence of solar activity in November 1960 was responsible for several solar particle events as the solar active region traversed the solar disk. This was the first time that one solar region was clearly associated with three individual relativistic solar proton events. The first of these events, on 12 November, was from a flare near central meridian; the "double humped" shape of the time-intensity profile as recorded by neutron monitors demonstrated the role of interplanetary shocks in the modulation of solar particles having energies greater than 500 MeV. The second event, on 15 November, also generated increases of over 100% as recorded by high latitude neutron monitors. The third event of this sequence, on 20 November, was apparently from this same region which had rotated over the western hemisphere of the sun. Optical observations of a solar prominence on the western limb in time association with the particle increase identified that solar activity as much as 30° behind the western limb, could be the source of a significant flux of relativistic protons at the earth. Some of the neutron monitors recorded an enhanced cosmic ray intensity for over 24 hours for each of these events.

The last relativistic solar proton events during the 19th solar cycle were again associated with a sequence of activity from a single active solar region with two ground-level en-

hancements recorded in July 1961. Subsequent analysis of the July 1961 events with peak fluxes of the order of 20% as recorded by neutron monitors, indicated that the total particle fluence above 10 and 30 MeV exceeded the fluence associated with the much larger (peak flux approximately 300%) relativistic particle event of 4 May 1960.

In anticipation of the International Years of the Quiet Sun (1964-1965) the NM-64 neutron monitor was developed (Carmichael, 1968). This monitor, with its better statistics and modern data recording techniques for more accurate time resolution, began to systematically and unambiguously detect solar cosmic ray ground-level enhancements with increases less than 10%. The two relativistic solar particle increases on 24 January 1967 coupled with spacecraft measurements at various positions around the sun removed all doubt that particles can be transported considerable distances in the solar corona since the solar longitude of the active region generally associated with this increase was more than 60° behind the western limb.

The sequence of solar activity during 2-7 August 1972 had major solar particle fluence observed by modern spacecraft instruments with the fluence exceeding 10^{10} particles cm^{-2} greater than 10 MeV. The cosmic radiation intensity enhancement on 4 August, which occurred approximately 6 hours after the associated flare, demonstrated unequivocally that interplanetary shocks can accelerate particles to GeV energies (Levy et al., 1976). This event also extended the recognized range of measurable effects on our planet with calculations that the ozone layer in the polar regions would have been depleted from the incidence of solar particles on the top of the atmosphere (Crutzen et al., 1975) that were subsequently substantiated using measurements from the Nimbus 4 satellite (Heath et al., 1977). The event of 30 April 1976, three months before the end of the 20th solar cycle, dispelled the once popular folklore that relativistic solar proton events did not occur near solar minimum.

The 21 August 1979 ground-level enhancement was also unique inasmuch as the parent flare lacked a prominent impulsive phase as observed by both solar radio and hard X-ray emission. This was in contrast to the intense electromagnetic emission observed from all previous relativistic solar proton events for which these radio/X-ray measurements were available (Cliver, et al., 1983).

The events of 7 May 1978 and 16 February 1984 allowed the determination of the complete solar particle spectra from the lower energies recorded by the spacecraft to the higher energies recorded by neutron monitors (Debrunner, et al., 1984, 1988). Although some high latitude neutron monitors recorded increases of over 100% for both of these particle events, the ten other events of the 21st solar cycle were considerably smaller with some of them having increases less than 10 percent.

From the beginning of routine space measurements until 1989 the sun has been relatively benign. In fact a number of the younger scientists and most of the scientific administrators questioned the ability of the sun to reproduce the major events of the 17th, 18th and 19th solar cycles, particularly since there were only two out of twenty-five ground-level enhancements in solar cycles 20 and 21 having increases greater than 100%. At the end of the 21st solar cycle there was an almost complacent attitude that the sun was relatively predictable and an object of only minimal interest for cosmic ray scientists.

Ground-Level Enhancements in 1989.

Solar cycle 22 started in October 1986. As this cycle has developed, it has defied all predictions of a benign uninteresting cycle. The solar activity, as measured by the sunspot number, is just under the largest value ever recorded with a current prediction

of sunspot maximum in March 1990 with a smoothed sunspot number of 191. The number of major solar X-ray flares and proton events is significantly higher than the previous cycle, and aurora has been seen as far south as Mexico and as far north as Sydney and Brisbane.

There was a 65 month lull between the last ground-level enhancement of the 21st solar cycle and the first relativistic solar particle event of the present cycle; this is the longest period of time between reported ground-level enhancements since neutron monitors began routine monitoring of the cosmic ray intensity in 1953. The first event of the 22nd solar cycle was so small that it almost went unnoticed. However, this event, on 25 July, was followed by a somewhat larger event on 16 August. Then on 29 September a major ground-level enhancement occurred - the largest since 23 February 1956 - to be quickly followed by three more respectable events in October, and another very small event in November. Indeed, when this activity finally subsided, we had experienced seven relativistic solar particle events within a four-month period making this an unprecedented sequence of solar cosmic ray events. In addition, four of these events were from solar activity in the same active region, albeit during two solar rotations. Table 1 presents preliminary solar optical and X-ray observations for each of these events as well as information on the cosmic ray increases as measured by high latitude sea level locations.

TABLE 1. Preliminary Information on Solar Flares in 1989 Associated with Ground-Level Enhancements in Cosmic Ray Intensity as Measured by Neutron Monitors

Date (UT)	Optical Flare				X-ray Event		Cosmic Rays	
	Onset	Location	Boulder Region	Imp.	Imp.	Duration (Hours)	Percentage Increase	Station
25 Jul	0838	N25 W84	5603	2N	X 2.6	0.5	3	Goose Bay
16 Aug	<0108	S18 W84	5629	2N	X20	13	13	Mawson
29 Sep	1047*	S-- W105	5698	--	X 9.8	4	372	Inuvik
19 Oct	1229	S27 E10	5747	4B	X13.0	>8	47	Mawson
22 Oct	1708	S27 W30	5747	2B	X 2.9	3.5	17	Goose Bay
24 Oct	1736	S30 W57	5747	3B	X 5.7	9	96	Inuvik
15 Nov	0652*	N11 W26	5786	3B	X 3.2	1.5	1.7	Deep River

Notes:

Solar and Optical Data from Preliminary Report and Forecast of Solar Geophysical Data, published weekly by the joint NOAA-USAF Space Environment Services Center, Boulder, Colorado.

Intensity increases based on five-minute data.

* X-ray onset times

The first solar cosmic ray event of the 22nd solar cycle occurred on 25 July 1989. This event was from a newly formed region on the sun which had produced only sub-flares for the seven days prior to this relativistic solar particle event. An approximate 3% increase at Goose Bay ($R_c = 0.64$ GV) as shown in Figure 1, and 2% at Hobart ($R_c = 1.84$ GV) indicates there were very few particles above 3 GV in this event.

The second event, on 16 August, forced a recalibration of the proton sensors on the SMS/GOES monitoring spacecraft (Zwicki, private communication). These channels are differential in energy and from inspection of the data the channels responding to the lower energies had an erroneous earlier onset than the channels responding to the higher energies. Although the sensors had been calibrated, the calibration did not include a response to a relativistic solar particle source. The time-intensity 1-8 Å soft X-ray emission was possibly the largest recorded by the SMS/GOES spacecraft; a value of X20 was assigned to this event during which the X-ray detector saturated. The Mawson neutron monitor recorded a 13% increase; particles of at least 4-5 GV were present as evidenced by the 5% increase at Climax (Rc = 2.99 GV). The increase detected at Mawson (Rc = 0.20 GV), Mt. Wellington (Rc = 1.80 GV) and Hobart (Rc = 1.84 GV) are shown in Figure 2.

890725 Goose Bay

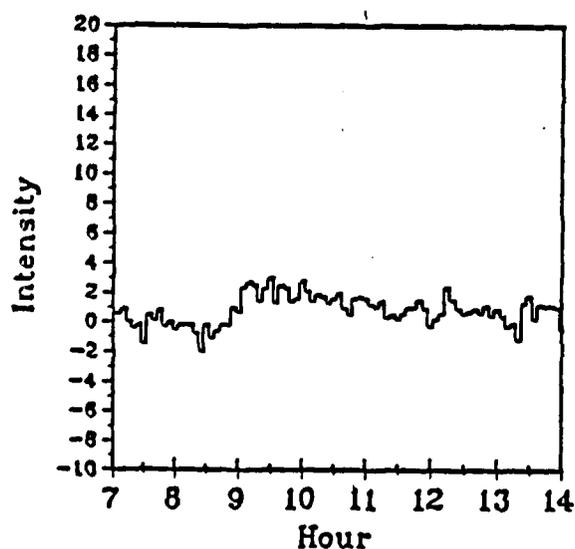


Figure 1. The 25 July 1989 relativistic solar cosmic ray event as observed at Goose Bay, Canada.

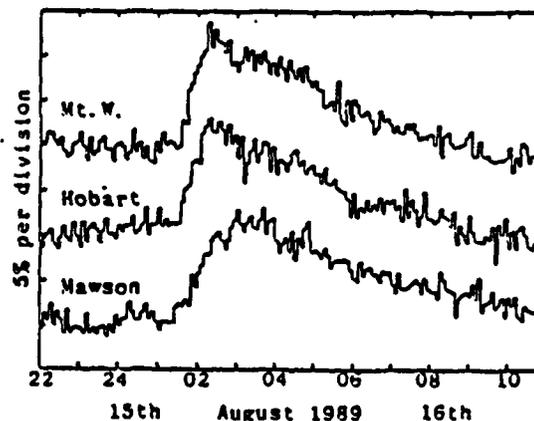


Figure 2. The 16 August 1989 relativistic solar cosmic ray event as observed at Mawson, Hobart, and Mt. Wellington. (From Humble et al., 1990)

After these preliminary "teasers" the sun was only moderately active until the event of 29 September which is of prime interest to the cosmic ray community. There are times when nature puts to a severe test man's presumed knowledge and technology. The event of 29 September is one of these times. To establish the solar circumstances, the region responsible for this event had rotated beyond the western limb of the sun, and consequently there are no preceding observations indicating that an extraordinary event was about to occur. In fact this region had only been moderately active as it traversed the solar disk with 61 sub flares and seven flares of importance 1. No X-class X-ray events had been associated with any of these flares, so the cosmic-ray community was not expecting an event that "announced" itself by arriving with a relativistic particle intensity that had not been observed at the earth for 33 years. The associated solar event has been placed at 105° W; even from this partially occulted location there was a measured X9.8 X-ray event with a four-hour duration. The Udaipur, India solar observatory reported that the solar activity was visible in H-alpha as a limb brightening, and the high resolution equipment at the US National Solar Observatory at Sacramento Peak showed spectacular loop structure lasting more than 10 hours.

This particle event had an extremely complex time-intensity profile as observed by neutron monitors. Preliminary data suggest it resembles the classic events observed by the ionization chambers in the events of 1942, 1946 and 1956. The standard cubical muon detectors at Deep River, Goose Bay and Inuvik, Canada recorded increases approximately 40% above background. By comparison the classic 4 May 1960 event had only a 4% increase in muon intensity. Figure 3 illustrates the standard cubical muon measurements at Deep River and Moscow.

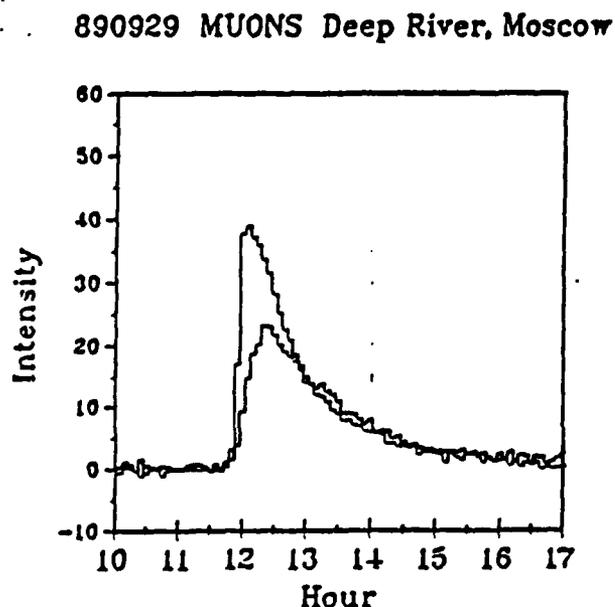


Figure 3. The 29 Sept. 1989 relativistic solar cosmic ray event as observed by the muon detectors at Deep River (top), and Moscow (bottom).

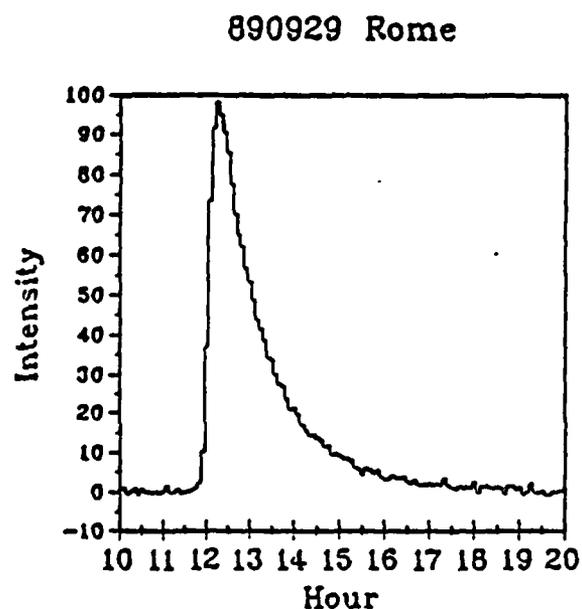


Figure 4. The 29 Sept. 1989 relativistic solar cosmic ray event as observed by the Rome ($R_c = 6.32$ GV) neutron monitor.

For the first time since 23 February 1956 an event was recorded by stations located at cutoff rigidities greater than 12 GV with increases reported at Huancayo ($R_c = 12.92$ GV) and Darwin ($R_c = 14.09$ GV). For all muon detectors and for neutron monitors at stations having relatively high rigidities (above approximately 5 GV) this looks like a classic solar proton event (see Figure 4). Our very preliminary analysis indicates that the event had an extremely hard spectrum during the initial phase. At stations with slightly lower rigidities, such as Deep River ($R_c = 1.14$ GV) and Kerguelen ($R_c = 1.14$ GV), interesting structural differences in the time-intensity profile are evident as seen in Figure 5. At polar latitudes these structural differences are most pronounced as illustrated in Figure 6. The hardness of this event is indicated by the fact it was observed by the underground muon detector at Embudo, USA whose 33 meter-water-equivalent mass absorber translates to a detection threshold of 19 GV. We estimate that particles of 25 GV were present in this event. In modern times (since 1950) this would rank as the second largest event seen by neutron monitors both in terms of total fluence above 1 GV and in terms of maximum energy of particles present.

890929 Deep River, Kerguelen

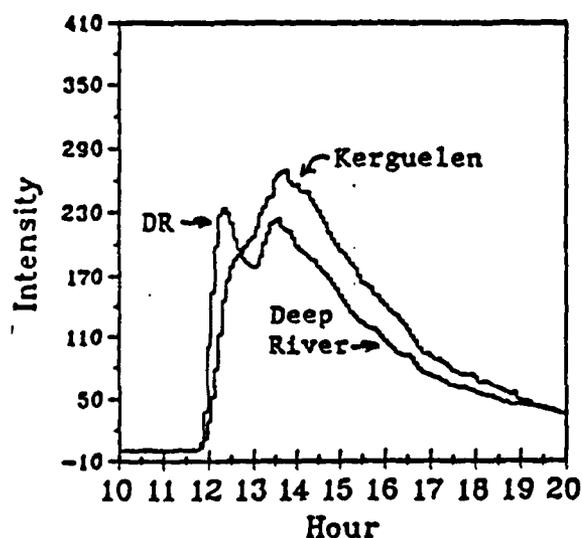


Figure 5. The 29 Sept. 1989 relativistic solar cosmic ray event as observed by the Deep River and Kerguelen neutron monitors.

890929 McMurdo, Thule

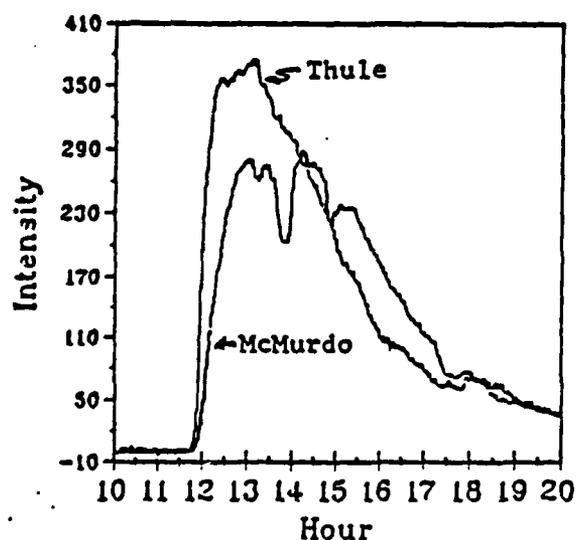


Figure 6. The 29 Sept. 1989 relativistic solar cosmic ray event as observed by the Thule and McMurdo neutron monitors.

The effect of this event on man's technology is notable. The radiation monitors on the high altitude Concorde supersonic aircraft flying between Paris and Washington reached alert levels for the first time in the history of their operation. The alert level is set at an equivalent of a chest X-ray; this does not indicate a hazard to passengers and crew. The Magellan spacecraft on its transit between earth and Venus experienced a 5% degradation in its solar cell power level output. In addition a number of spacecraft including Magellan observed interference in the guidance and command and control functions. In contrast to the relatively short duration events that have been occurring since 1960 some neutron monitors recorded enhanced flux for approximately 24 hours.

During the month of October the sun continued to demonstrate the limits of human ignorance by generating in one month more fluence than had been generated in either of the previous two solar cycles as shown in Table 2. Man's ability to forecast events of this type is severely lacking as indicated by the forecast of solar and geomagnetic activity reproduced in Figure 7. The solar active region responsible for the October activity which included three ground-level enhancements, was located on the sun in the same vicinity as the region associated with the 29 September event.

**Forecast of Solar and Geomagnetic Activity
18 October 1989 - 13 November 1989**

Solar activity is expected to fluctuate about the moderate level the next 27 days. Episodes of high activity are possible early in the forecast period as Region 5747 may generate an isolated X-class flare.

Figure 7. Forecast of Solar and Geomagnetic Activity for the period 18 October - 13 November 1989 (Preliminary Report, 1989)

The onset time of the relativistic proton event of 19 October was dependent on the asymptotic viewing direction of the neutron monitor. This indicates that some anisotropy was present in spite of the fact that the flare responsible for this event was located east of central meridian. Increases greater than 40% were recorded by neutron monitors in the polar regions, particles with at least 5 GV were present, and the event, at neutron monitor energies, lasted 24 hours. The increase recorded by the Deep River neutron monitor is shown in Figure 8.

891019 Deep River

TABLE 2. Proton Fluence Comparisons

Solar Cycle	Fluence (> 10 MeV) (Particles/cm ²)
19	6.7×10^{10}
20	2.5×10^{10}
21	1.8×10^{10}

22	
Mar 1989	0.2×10^{10}
Sep 1989	0.8×10^{10}
Oct 1989	2.8×10^{10}
	3.8×10^{10}

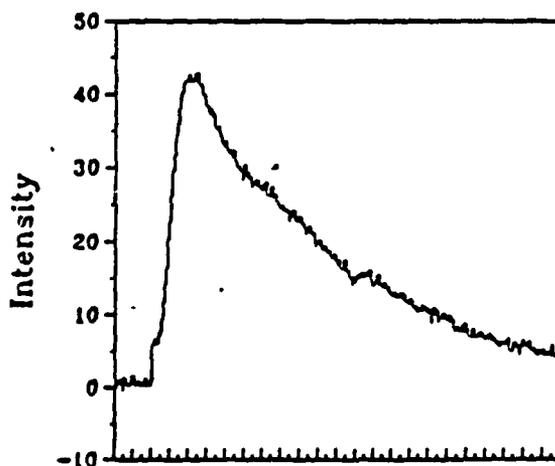


Figure 8. The 19 October 1989 solar cosmic ray event as observed by the Deep River neutron monitor.

The 22 October relativistic solar proton event exhibited initial particle anisotropy and had a very structured time-intensity profile until maximum intensity. Increases between 10 and 20% were recorded at high latitude stations. This event, having a duration of 8-12 hours as measured by neutron monitors, does not appear to have particles greater than approximately 5 GV present. The increase recorded by the Goose Bay neutron monitor is shown in Figure 9.

The final event of the October sequence, on 24 October, exhibited a slower rise than the 19 October event even though the associated flare was much closer to the footpoint of the nominal interplanetary magnetic field line connecting the earth with the sun. Increases of 80-100% were recorded at high latitudes, and mid-latitude stations having threshold rigidities greater than 6 GV reported small enhanced intensities. The relativistic particle increase had a duration of approximately 24 hours. The increase recorded by the Goose Bay neutron monitor is shown in Figure 10.

The severe particle environment throughout this period again caused interference with spacecraft operations. As an example, the Magellan spacecraft lost an additional 7% of the output of its solar cell arrays which might be expected considering that in one month this spacecraft experienced more than a nominal solar cycle's worth of radiation exposure. The extreme activity associated with this active solar region as it traversed the solar disk in October is shown by the fact that it produced over 100 flares and 53 X-ray events (importance C or greater).

The sun continued to intrigue us with yet another ground-level enhancement, this one a small event on 15 November with increases of approximately 2% recorded by high latitude neutron monitors.

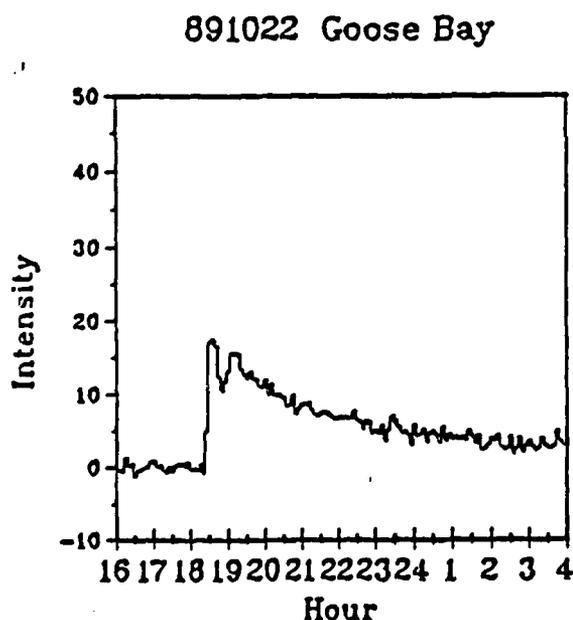


Figure 9. The 22 October 1989 relativistic solar cosmic ray event as observed by the Goose Bay neutron monitor.

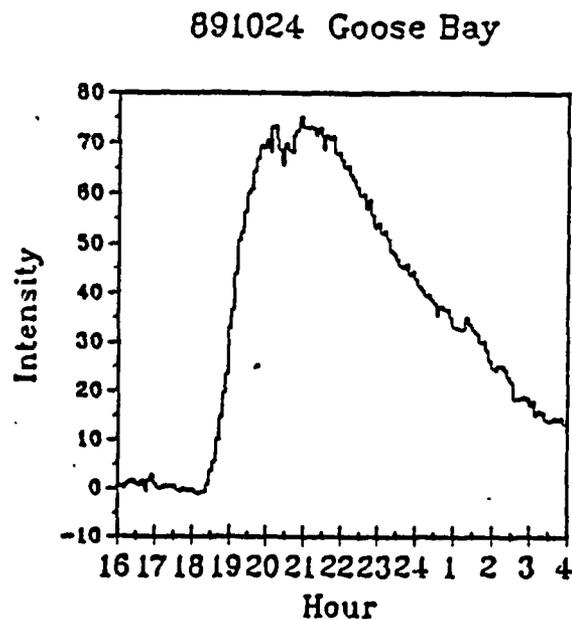


Figure 10. The 24 October 1989 relativistic solar cosmic ray event as observed by the Goose Bay neutron monitor.

Comparison with Previous Events.

The relativistic solar proton events that we have experienced in September and October 1989 are reminiscent of the events in the 17th, 18th and 19th solar cycles - specifically the events in 1942, 1946, and 1956. Even the large fluence events of 1960 did not generate significant increases on muon detectors; thus it appears that the major relativistic solar proton events between 1957 and 1988 had a somewhat softer spectra than the earlier major events.

The question now arises - What is "normal" solar activity when it comes to relativistic solar proton events? Is it the type of activity that occurred in the 17-19th solar cycles with large fluxes of long duration and the acceleration of protons to energies greater than approximately 10 GeV or is it the relatively benign aspects of the 20th and 21st solar cycles with considerably smaller events of short duration? The events of 1989 will be extensively studied over the next several years. These events give us an opportunity to better understand solar proton acceleration, release and propagation characteristics, thus contributing to the knowledge of our nearest star - the sun.

Acknowledgements.

I was asked to contribute to this highlight session in November 1989. Unfortunately the terminal illness of my father in December and his death on New Year's Day precluded my concentration on this work until after his funeral. I decided to attend this conference after his death as I know he would have wanted me to participate; therefore I dedicate this paper to his memory. I am most grateful to my husband, Don F. Smart, who prepared many of my figures and critiqued both the oral presentation and the written manuscript. I also am grateful to Ms. Louise C. Gentile who assembled many of the data sets and also helped in preparing the figures. Finally, I gratefully acknowledge the cooperation of many cosmic ray scientists who have permitted me to use their data for this overview prior to their own publication.

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