AD-A256 685

18 August 1992

Reprint

Long-Term Solar and Cosmic Radiation Data Bases

PE 61102F
PR 2311
TA G4
WU 02

M.A. Shea, D.F. Smart

Phillips Lab/GPSG
Hanscom AFB
Massachusetts 01731-5000



PL-TR-92-2213

Reprinted from J. Geomag. Geoelectr., 43, Suppl., 855-863, 1991

Approved for public release; Distribution unlimited

The cosmic radiation that reaches the earth is inversely correlated with solar activity as represented by the sunspot number. Thus one of the longest solar-terrestrial data records (solar data) has been combined with one of the shortest data records (cosmic radiation) to learn more about the cosmic radiation that reaches the earth's environment. A brief summary of solar and cosmic radiation data records and several interesting scientific results that have been found with these data are presented.

Solar activity, Solar-Terrestrial physics, Cosmic radiation, Sunspot numbers, Solar-terrestrial data

9

| | | | |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | SAR |

PL-TR-92-2213

J. Geomag. Geoelectr., 43, Suppl., 855–863, 1991



# Long-Term Solar and Cosmic Radiation Data Bases

M. A. SHEA and D. F. SMART

*Space Physics Division, Geophysics Laboratory, Hanscom AFB, Bedford, MA 01731-5000, U.S.A.*

(Received September 11, 1990; Revised October 19, 1990)

The cosmic radiation that reaches the earth is inversely correlated with solar activity as represented by the sunspot number. Thus one of the longest solar-terrestrial data records (solar data) has been combined with one of the shortest data records (cosmic radiation) to learn more about the cosmic radiation that reaches the earth's environment. A brief summary of solar and cosmic radiation data records and several interesting scientific results that have been found with these data are presented.

## 1. Introduction

Solar observations comprise one of the longest data records in solar-terrestrial research with limited reconstructed sunspot data since 1610 and reliable sunspot data from 1848 (MCKINNON, 1987). The measurement of cosmic radiation impinging on the top of the atmosphere is probably the last significant solar-terrestrial data record initiated prior to the space era. Ionization chamber measurements of cosmic radiation began in 1933 with standardized neutron monitor measurements starting in 1953. Since solar activity and cosmic radiation correlate inversely with an approximate 11-year cycle, it is inappropriate to discuss cosmic radiation records without first considering the long-term solar cycle.

## 2. Solar Data

The sun is a controlling factor on many aspects of our terrestrial environment. The latitude of the location of sunspots as a function of time, the so-called "butterfly diagram", is plotted in the top part of Fig. 1 for the past 10 solar cycles. The smoothed sunspot number for this time period is illustrated in the bottom part of this figure. Sunspot numbers, as derived in 1848 by Wolf, are determined by adding 10 times the number of sunspot groups to the total count of individual spots. Because these Wolf numbers vary considerably from one month to the next, a "smoothed" 13-month running mean of monthly means was derived to typify the solar cycle. Smoothed sunspot numbers are easy to calculate from the Wolf sunspot numbers, are easy to use, and are readily accessible. Consequently many scientists use this number—for better or worse—as an ordering parameter or fiducial mark for various solar-terrestrial analyses.

Figure 2 shows that different types of solar activity such as solar flares and metric type II radio emission, closely follow the sunspot cycle as characterized by the mean sunspot number. Although the world-wide monitoring of solar activity on a 24-hour basis did not

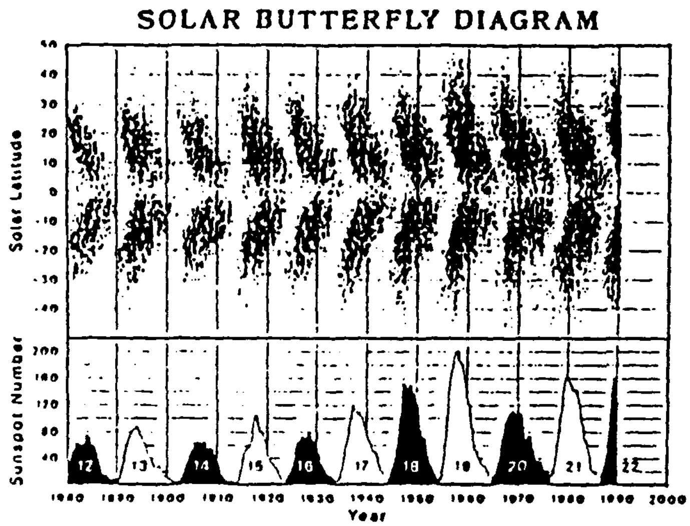


Fig. 1. (Top) The solar latitude of sunspots from 1880 until 1990 (after the original drawings by E. W. MAUNDER). This diagram shows spots in any given latitude at any given time in the sun's activity cycle. Successive spot groups erupt at slightly lower latitudes in each hemisphere and with increasing (and then decreasing) frequency to form a pattern suggestive of pressed butterfly wings. The subtle trends in sunspot eruption captured here emerged only through a long-term observation program. (Bottom) The smoothed sunspot number from 1880 until 1990. This is the most common value used to isolate the solar cycle extremes (Figure courtesy of D. C. Wilkinson).

become routine until the International Geophysical Year, a reasonable data base for solar flares exists since 1932; the solar radio data are much more recent. To turn to even more recent data, Fig. 2 also shows the frequency of occurrence of coronal mass ejections for the past 1 1/2 solar cycles. These measurements, initiated with an experiment on SKYLAB, were continued on the P78-1 and Solar Maximum Mission (SMM) spacecraft. Although these satellite measurements have ceased, this limited data base has been extensively used in various analyses, and it is now known that coronal mass ejections play an important role on the status of the interplanetary medium and the geophysical environment.

Finally, at the earth, and using the geomagnetic data records, we see that the occurrence of magnetic storms generally follows the sunspot cycle as illustrated in Fig. 3. The storms, as typified by the number of days the $A_p$ daily index of global magnetic activity exceeded 40, appear to have two peaks; the first related to solar activity and associated interplanetary shocks encompassing and travelling past the earth, and the second associated with recurrent high speed solar streams from coronal holes.

Other solar data bases exist that may ultimately prove to correlate better with solar-terrestrial phenomena than the smoothed sunspot number. For example, sunspot area, actually preferred by Wolf over his derived sunspot number, may be a better correlator for solar phenomena that emit turbulent disturbances into the interplanetary medium. Unfortunately these data are late in being produced, are not easily accessible, and are not readily distributed. Although the original records can be utilized to obtain a consistent long-term data base, the intense effort required and the absence of recent values, discourage the use

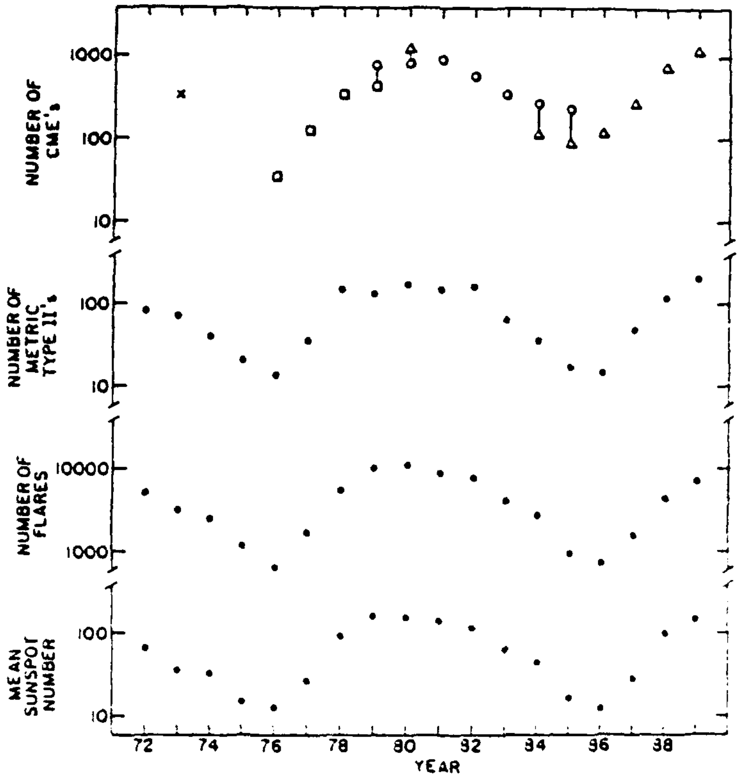


Fig. 2. The annual mean sunspot number, counts of solar flares, number of metric Type II solar radio emissions, and coronal mass ejections from 1972 through 1989. This figure represents a short-term record of solar cycle effects at sequentially higher altitudes (from the bottom of the figure to the top of the figure) above the sun's surface. For the coronal mass ejection portion of the figure, the "X" represents data from SKYLAB, the squares represent data from HELIOS, the open circles represent data from the SOLWIND experiment on P78-1, and the triangles represent data from the Solar Maximum Mission (Data from COFFEY, 1990, and D. F. WEBB, 1990).

of these data.

The sunspot areas have been separated by solar hemisphere since 1874. These data are also difficult to locate especially since the Greenwich Observatory terminated their monitoring program in 1976. Total sunspot areas organized by hemisphere may become increasingly important if studies of hemispheric differences such as those identified by SHEA *et al.* (1989) and KING (1991) are pursued.

Another solar data base being extensively used in various analyses is the source surface magnetic fields (HOEKSEMA and SCHERRER, 1986). Magnetic fields at the solar surface are very complex; however, after the observed photospheric fields are modeled and extrapolated to 2.5 solar radii, the resultant source surface field structures are much more uniform. These source surface magnetic fields have been shown to be representative of the fields transported into the interplanetary medium. The change from one magnetic polarity to the other indicates the position of the heliospheric current sheet which extends throughout the heliosphere. Source surface magnetic fields are quite regular at solar minimum, but they become

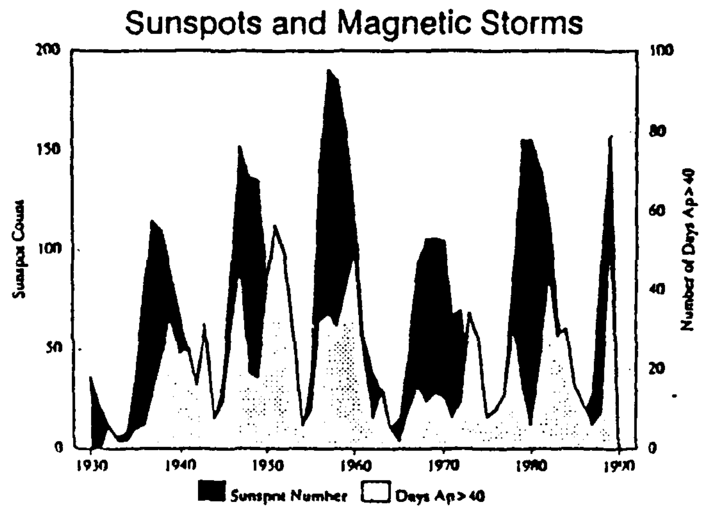


Fig. 3. The number of days when the $A_p$ daily index of global magnetic activity exceeds a value of 40 (lightly shaded curve) compared with the annual smoothed sunspot number (dark curve). $A_p$ values greater than 40 are indicative of moderately disturbed conditions (Figure courtesy of J. H. Allen).

increasingly complex as the solar cycle progresses from minimum to maximum. Source surface magnetic fields are used to predict the polarity of the interplanetary magnetic field at various positions in space. Observations of the interplanetary magnetic field polarity are highly correlated with the predictions from the source surface maps transported to the position of the earth. This is an example of a relatively new solar data base which, when it became routinely available and readily accessible, was enthusiastically utilized by researchers for many kinds of analyses not envisioned when the observations began.

There are, of course, many other data bases of solar phenomena that are used for a variety of purposes. For example, the presence of coronal holes at the solar limb can be inferred by the relative intensity of coronal green line emissions; coronal holes on the disk can be inferred by Helium 10830 measurements. Other solar data bases, archived at World Data Center A for Solar-Terrestrial Physics, include 10.7 cm solar radio flux (since 1947), fixed frequency solar radio bursts (since 1960), calcium plage regions (since 1962), coronal index of solar activity (since 1964), regions of solar activity (since 1969), total solar irradiance (since 1978), and solar Lyman-alpha flux (since 1982).

## 3. Cosmic Radiation Data

Routine measurement of high energy cosmic radiation intensity started in 1933 using an ionization chamber in Innsbruck, Austria. Unfortunately, the "atmospheric penetration energy threshold" of these muon detectors (approximately 6 GeV) was so high that it was extremely difficult to determine the magnitude of the variations in the cosmic ray intensity caused by solar activity. Neutron monitors, with their much lower energy threshold, have been in routine operation since 1953. These detectors measure cosmic radiation from an atmospheric detection threshold of about 450 MeV, if located at high latitudes, to a geomagnetic cutoff threshold of approximately 15 GeV, if located in the equatorial latitudes. The ability to measure particle radiation in the GeV range cannot be duplicated by space-borne instruments, giving rise to the expression that neutron monitors are sensors on spacecraft EARTH.

Here we will consider cosmic ray detectors to measure two components of cosmic radiation. First they respond to the background galactic cosmic radiation entering the heliosphere from outside the solar system—a particle flux modulated within the heliosphere by effects of the solar activity cycle. Superposed on this background cosmic radiation are short-lived intensity perturbations such as decreases associated with solar-induced interplanetary transients and increases associated with solar flare accelerated protons.

Cosmic radiation intensity measured for over three solar cycles by the longest continually operated neutron monitor at Climax, Colorado, U.S.A. is shown in Fig. 4. A comparison with the solar cycle as illustrated by the sunspot number in Fig. 1, shows that the maximum cosmic ray intensity occurs near sunspot minimum when solar activity is low and there is minimum turbulence in the heliosphere. As solar activity increases, solar-induced perturbations in the heliosphere impede the transport of particles to the earth, and the cosmic radiation intensity decreases.

The shape of this intensity curve—from a smooth curve to a square wave to a smooth curve—has been the subject of intense theoretical research concerning particle entry into and transport through the heliosphere as evidence for a 22-year cycle controlled by the polarity of the solar magnetic field. Two relatively recent results indicate that (1) excessive solar activity

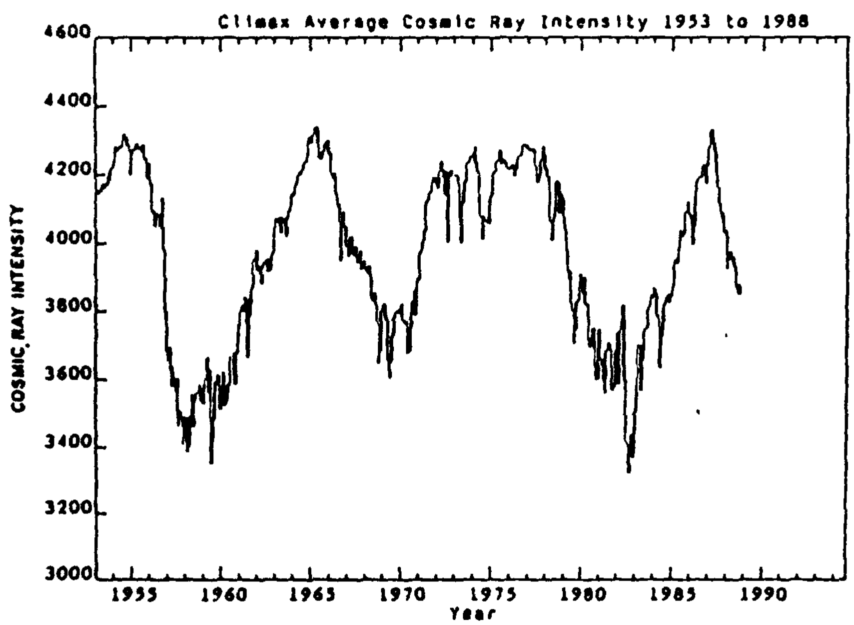


Fig. 4. The galactic cosmic ray intensity as measured by the neutron monitor located at Climax, Colorado. The 11-year solar cycle effect is clearly present, although inversely related to sunspot activity (Data, courtesy of R. Pyle).

during solar minimum may have contributed to the reduced intensity in 1976–1977 as shown in Fig. 4 (SHEA and SMART, 1990a), and (2) the size of the modulation region in the heliosphere, and hence the amount of modulation, is partially controlled by the tilt of the interplanetary current sheet (LOCKWOOD and WEBBER, 1988).

There have been 46 known relativistic solar proton events since 1955. These events contain solar particles with energies greater than 450 MeV; some events such as those in 1956 and 1989 had particles with energies in excess of 15 GeV. Figure 5 gives the number of events each year as a function of the sunspot cycle. The dots around the circle on the right side of this figure show the solar longitude of each flare considered to be the source region of the high energy particle acceleration. As can be seen, flares from well behind the solar limb can accelerate high energy particles that reach the earth. The intensity of these relativistic solar proton events can range from a few percent to several thousand percent of the cosmic ray background. The duration, which can be a few hours or more than a day, is assumed to be related to the solar acceleration and release processes and the propagation characteristics in the interplanetary medium. Figure 6 shows the cosmic radiation time-intensity profile for the largest events of the 21st and 22nd solar cycles. Using data obtained by the Kerguelen Island neutron monitor it can be seen that while the magnitude of these events is similar, the duration is considerably different, a phenomenon not yet understood.

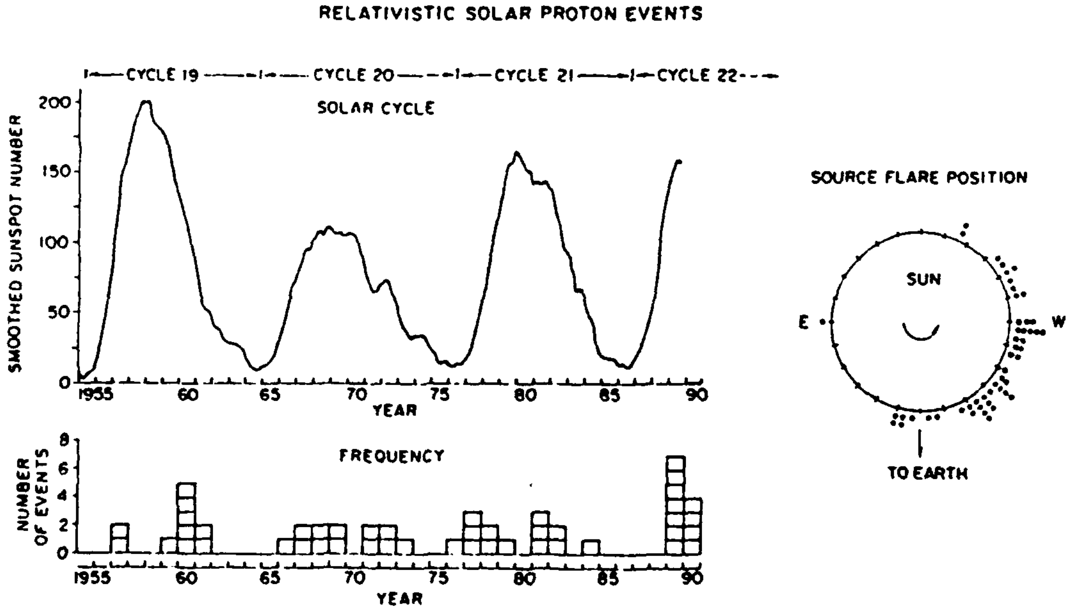


Fig. 5. The observed high energy solar proton events ($E > 450$ MeV) over three solar cycles. The top part of the figure shows the smoothed sunspot number. The bottom part of this figure shows the number of relativistic solar proton events (ground-level solar cosmic ray events) each year. The solid dots in the right part of the figure show the location on the sun considered to be the source region of each of these events. The four open circles are the assumed location of the source region for the relativistic solar proton events in 1942 (two events), 1946 and 1949. From July 1989 through May 1990 there has been an unprecedented number of ground-level solar cosmic ray events with 11 being recorded by neutron monitors on the surface of the earth.

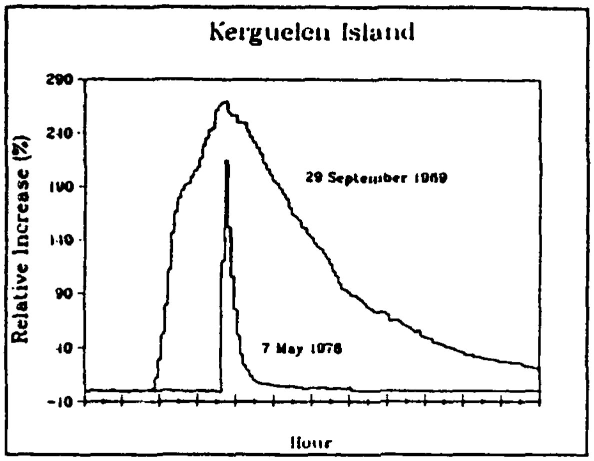


Fig. 6. Comparison of the magnitude (percentage above background cosmic ray intensity) and duration of the largest relativistic solar proton event in the 20th or 21th solar cycles (7 May 1978) with the largest proton event (to date) in the 22nd solar cycle (29 September 1989). These measurements were obtained from the neutron monitor at the Kerguelen Islands.

## 4. Satellite-Observed Solar Proton Events

Although not considered "cosmic radiation" because of the lower energy involved, we are including, for completeness, solar proton events above a 10 MeV threshold of 10 protons/cm$^2$-sec-ster. These data have been assembled using spacecraft measurements and, in the era before spacecraft, using measurements from various ground-based detectors such as riometers, ionosondes, and neutron monitors. A total of 218 solar proton events meeting the above criteria have been identified between 1954 and 1986 (SHEA and SMART, 1990b).

From solar proton flux measurements obtained during solar proton events, it is possible to calculate the fluence for each event. By summing these fluence values the total solar proton fluence detected at the earth during the entire solar cycle can be determined. A comparison of the solar proton fluence for the past three solar cycles shows there was more fluence in the 19th cycle by more than a factor of two then for either the 20th or 21st cycles. However, the fluence for three episodes of activity in 1989 has already exceeded the fluence for either the 20th or 21st cycles. These values are necessary for space station studies and for planning manned missions to the moon and Mars.

## 5. Cosmic Ray Measurements and Geomagnetic Parameters

Finally, cosmic radiation measurements are also used in conjunction with geomagnetic parameters. One common measurement is the cosmic ray intensity as a function of geomagnetic cutoff during solar minimum. During a latitude survey from South Africa to New York City in 1976, an unexpected discrepancy was found in a plot of the cosmic ray intensity against geomagnetic cutoff values along the airplane flight path. This discrepancy consisted of a statistically significant difference in the counting rate for locations having the same computed cosmic ray cutoff but in the opposite hemispheres. The cutoff rigidity values had been determined using a geomagnetic field model appropriate for 1965—11 years earlier than the experimental measurements. When the geomagnetic cutoffs were recalculated for 1976, the intensity data for both hemispheres were comparable for equal cutoff rigidity values. From these measurements, discussed by SHEA and SMART (1990c), it was concluded that the secular change in the geomagnetic field is sufficiently large that it affects the long-term cosmic radiation intensity measurements in some regions of the world. Therefore, the appropriateness of geomagnetic field values, another frequently used parameter in solar-terrestrial analyses, must be carefully evaluated for each specific analysis, especially if the study involves a long-term data base.

## 6. Concluding Remarks

The presently available long-term solar and cosmic radiation data bases have already provided considerable insight into how the sun controls many aspects of the terrestrial and heliospheric environment. However, for increased understanding of our own planet and for the exploration of other planets there is still much to learn about the sun, its processes and how it controls particle radiation and other geophysical and heliospheric phenomena.

The time scales associated with solar activity from the basic 11-year cycle to perhaps much longer cycles necessitate very long-term monitoring of the sun and related phenomena such as cosmic radiation intensity. As our understanding of solar-terrestrial and interplanetary phenomena increases, new data will be combined with the older data to test new ideas and theories that are developed. As these newer ideas and theories are accepted, new measurement techniques will be suggested, tried, evaluated and approved by the scientific community for such is the nature of scientific research.

The authors gratefully acknowledge the comments of the two referees, J.A. McKinnon and D.F. Webb, the data provided by D.F. Webb and R. Pyle used in Figs. 2 and 4, the figures provided by J.A. Allen and D.C. Wilkinson, and the assistance of L.C. Gentile in generating Figs. 4 and 6.

## REFERENCES

COFFEY, H. E. (Ed.), Solar-Geophysical Data, Report No. 551, Part II, p. 30, National Geophysical Data Center, NOAA, Boulder, Colorado, 1990.

HOEKSEMA, J. T. and P. H. SCHERRER, The Solar Magnetic Field—1976 Through 1985, Report UAG-94, Nat. Geophys. Data Cntr., NOAA, Boulder, Colorado, 1986.

KING, J. H., Long term solar wind variations and associated data sources, this volume, 1991.

LOCKWOOD, J. A. and W. R. WEBBER, Characteristics of the 22-year modulation of cosmic rays as seen by neutron monitors, *J. Geophys. Res.*, 93, 8735–8740, 1988.

MCKINNON, J. A., Sunspot Numbers: 1610–1986 Based on the Sunspot Activity in the Years 1610–1960, Report UAG-95, National Geophysical Data Center, NOAA, Boulder, Colorado, 1987.

SHEA, M. A., D. F. SMART, D. B. SWINSON, J. E. HUMBLE, J. A. MCKINNON, and C. C. ABSTON, Solar activity asymmetries and their possible effect on the high energy cosmic ray perpendicular gradient, *Adv. Space Res.*, 9, (4)221–(4)224, 1989.

SHEA, M. A. and D. F. SMART, The effect of solar activity on the cosmic ray intensity at solar minimum, 21st International Cosmic Ray Conference, *Conference Papers*, 6, 13–17, 1990a.

SHEA, M. A. and D. F. SMART, A summary of major solar proton events, *Solar Phys.*, 127, 297–320, 1990b.

SHEA, M. A. and D. F. SMART, The influence of the changing geomagnetic field on cosmic ray measurements, *J. Geomag. Geoelectr.*, 1990c (in press).
WEBB, D. F., The solar cycle variation of the ratios of CMEs and related activity, *Adv. Space Res.*, 1990 (in press).