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Space Weather and the Ground-Level Solar Proton Events of the 23rd Solar Cycle

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Abstract Solar proton events can adversely affect space and ground-based systems. Ground-level events are a subset of solar proton events that have a harder spectrum than average solar proton events and are detectable on Earth's surface by cosmic radiation ionization chambers, muon detectors, and neutron monitors. This paper summarizes the space weather effects associated with ground-level solar proton events during the 23rd solar cycle. These effects include communication and navigation systems, spacecraft electronics and operations, space power systems, manned space missions, and commercial aircraft operations. The major effect of ground-level events that affect manned spacecraft operations is increased radiation exposure. The primary effect on commercial aircraft operations is the loss of high frequency communication and, at extreme polar latitudes, an increase in the radiation exposure above that experienced from the background galactic cosmic radiation. Calculations of the maximum potential aircraft polar route exposure for each ground-level event of the 23rd solar cycle are presented. The space weather effects in October and November 2003 are highlighted together with on-going efforts to utilize cosmic ray neutron monitors to predict high energy solar proton events, thus providing an alert so that system operators can possibly make adjustments to vulnerable spacecraft operations and polar aircraft routes.

Keywords Space weather · GLEs · Ground-level cosmic ray events · Solar protons

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1 Introduction

The term "space weather" means different things to many people: reduced satellite operations; upsets in electronic circuits on spacecraft; solar cell degradation; possible disruption in polar aircraft flights; radio communication problems from perturbations in Earth's ionosphere; and impacts on electrical power grids during major geomagnetic storms. Even everyday items such as television reception and cell phone usage can be impaired during a major perturbation of the spatial environment surrounding Earth. The space weather effects can roughly be divided into two categories: those effects quickly and directly associated with solar activity, and those effects resulting from the impact of solar activity-generated interplanetary coronal mass ejections (ICMEs) on Earth's magnetosphere.

While space weather effects are generally associated with some type of solar activity, not all space weather effects can be attributed to solar proton events (SPEs).[1] Major solar activity from the central meridian of the Sun typically generates a plethora of emissions that impact Earth. These include solar X-rays, solar radio emissions, solar plasma,[2] fast coronal mass ejections (CMEs), and the energetic solar particles (ions in the MeV and GeV energy range and electrons in the keV and MeV energy range). The transport of fast CMEs (those with speeds at least double the average solar wind speed) between the Sun and Earth usually takes 1–2 days depending upon the speed of the ejection. The slower coronal mass ejections (those with speeds not significantly faster than the average solar wind speed) take 3–4 days to arrive at 1 AU. When the interplanetary coronal mass ejection interacts with the magnetosphere, massive amounts of energy are transferred resulting in electrical currents flowing in the magnetosphere generating enhanced magnetic fields that produce the phenomenon known as a geomagnetic storm.

The amount of energy transferred from the CME plasma to Earth's magnetosphere is dependent upon the orientation of the magnetic field embedded in the plasma. If the orientation of the interplanetary magnetic field is southward, then massive amounts of energy are transferred into the magnetosphere intensifying the current systems flowing in the magnetosphere and generating the geomagnetic storm. If the orientation of the interplanetary magnetic field is northward, then a lesser amount of energy is transferred. See Akasofu (2011) for a review of the CME-geomagnetic storm relationships.

The position of the solar activity on the Sun has a strong influence on the resulting space weather effects at Earth (Shea and Smart 1993, 1994). From an energetic particle viewpoint, the solar wind propagation outward from the Sun combined with solar rotation, results in an Archimedean spiral configuration of the interplanetary magnetic field. Solar particles from activity on the western sector of the Sun, or even slightly behind the western solar limb as viewed from Earth, has a "good" connection to Earth along the interplanetary magnetic field Archimedean spiral path as illustrated in Fig. 1.

Solar plasma and particle emissions from the central portion of the Sun often have a more significant effect on Earth's magnetosphere than similar emissions from the eastern or western portion of the Sun since the coronal mass ejections effectively propagate radially

[1] The designation of SPE is slightly ambiguous. Some authors use SPE to designate solar proton events while other authors use SPE to designate solar particle events. The abbreviation SEP is also frequently used to define either solar energetic protons or solar energetic particles. In this manuscript we use the term solar particles to include all particulate emissions from the Sun and SPE to designate solar proton events.

[2] The average solar wind plasma proton energy is approximately 1 keV; the average solar wind electron energy is approximately 100 eV.

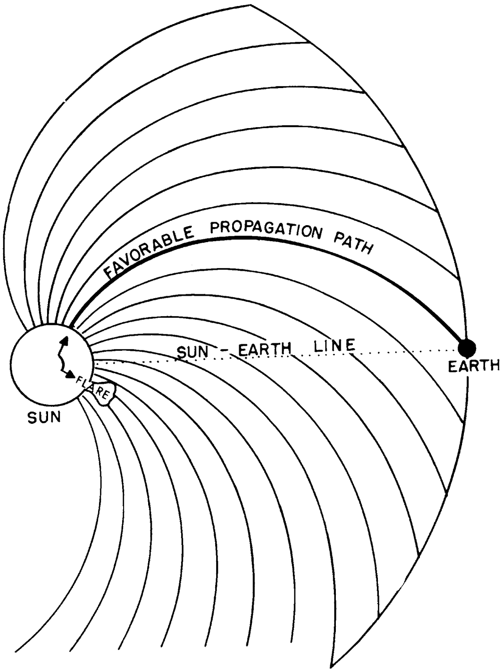

Fig. 1 Illustration of the "Archimedean spiral path" configuration of the interplanetary magnetic field as the Sun rotates. Energetic particles flow along the interplanetary magnetic field lines

outward from the Sun. Similar solar plasma and particle emissions from the eastern hemisphere of the Sun normally have less effect on Earth's magnetosphere than activity from the western solar hemisphere.

The generic term solar proton event is understood to mean any increase in the observed proton flux above the ambient background as the result of solar activity. At low energies, 1 MeV range and below, there are many observed solar proton increases, but they have relatively little effect on the geospace environment. In the 1–10 MeV range, a large increase in the proton flux primarily affects only Earth's polar ionosphere environment. In the 10–100 MeV range, the solar protons have enough energy to penetrate deep into Earth's ionosphere and can generate a significant increase in the electron density in the ionosphere. The NOAA Space Weather Prediction Center has defined a solar proton event[3] as having a flux of >10 MeV protons greater than 10 particles $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr})^{-1}$. In the 100–1000 MeV range, there is sufficient energy to penetrate through the ionosphere into the stratosphere. In addition, the "knock on effect" will result in secondary nucleons from interaction with the atmospheric atoms. This increases the total particle flux in the atmosphere, thus making a significant contribution to the total ionization in the atmosphere. In the GeV energy range, there is sufficient energy for "pair production" generating additional energetic nuclei that can penetrate through the atmosphere to Earth's surface.

The term cosmic ray ground-level events (or ground-level enhancements as frequently called) refer to an increase in the cosmic radiation flux as measured by ground-level detectors such as neutron monitors, ionization chambers and muon detectors. In order to generate a ground-level enhancement (GLE), the solar energetic ions must have sufficient energy to penetrate Earth's magnetic field and then interact in the atmosphere generating nuclear in-

[3] http://www.swpc.noaa.gov/info/Glossary.html.

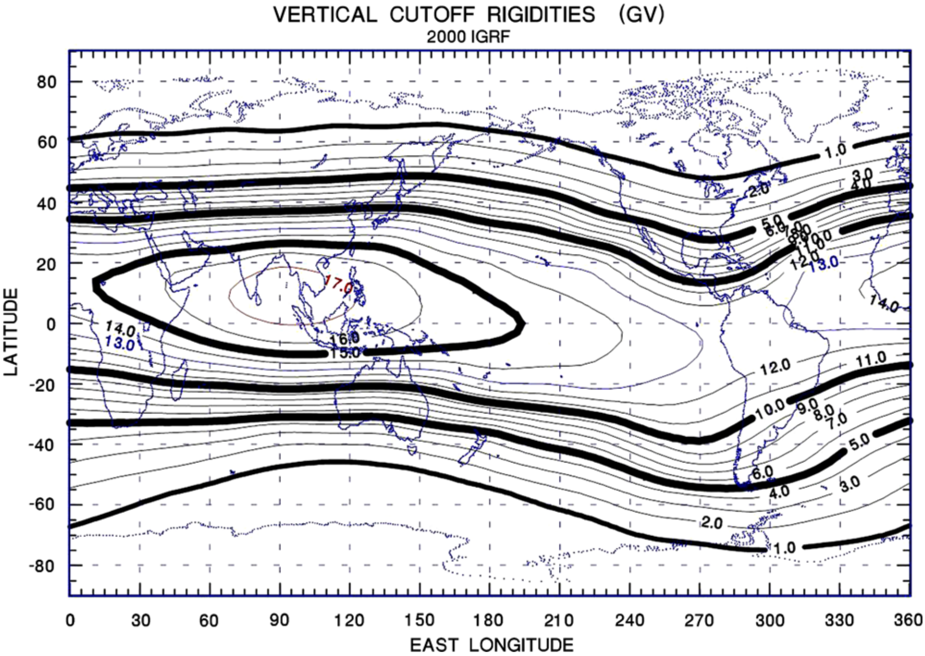

Fig. 2 A world map of vertical cutoff rigidity contours for Epoch 2000. The contours are in units of rigidity (GV)

teractions such that a cascade of secondary particles produce a measurable increase in the observed total cosmic ray intensity at ground level. See Ryan et al. (2000) for a review. The geomagnetic field shields Earth from the lower energy particles. The amount of shielding is a function of geomagnetic latitude with minimum (zero) shielding in Earth's polar regions and maximum shielding in the equatorial regions. Figure 2 illustrates the geomagnetic cutoff rigidity contours for Epoch 2000 (Smart and Shea 2009). Protons with energies greater than approximately 450 MeV can generate a nuclear cascade that can penetrate to the surface of Earth in the polar regions. It takes approximately 15 GeV of energy to penetrate through Earth's magnetosphere in the equatorial regions and then generate the nuclear cascades in the atmosphere such that an increase above the cosmic radiation background intensity can be detected by cosmic ray instrumentation.

The acceleration of protons to GeV energies is not thoroughly understood. The papers in this issue of Space Science Reviews are summaries of our knowledge. The process appears to be associated with the rapid release of energy in the solar magnetic fields (Parker 2009) resulting in shocks in the solar corona and interplanetary space. Ground-level events can be associated with a significant solar flare on the visible disk or a presumed flare from an active region that may not be on the visible solar disk. During the 23rd solar cycle, all of the GLEs were also associated with fast coronal mass ejections (Gopalswamy et al. 2005, 2010, 2012).

Ground-level enhancements are relatively rare with approximately 15 events per solar cycle (Shea and Smart 1990, 2008). There were 16 GLEs in solar cycle 23; these are listed in Table 1. Gopalswamy et al. (2012) and Kahler et al. (2012) provide details of the associated solar radio, solar X-ray, solar flare and CME data. Nitta et al. (2012) provide "snapshot illustrations" for each of the GLEs in Table 1. In this paper we will discuss the space

Table 1 Ground-level enhancements in the 23rd solar cycle

GLE number*	GLE date			Solar coordinates of active region	Maximum percent increase**	Time of first maximum		Duration Hrs >10 %	Rigidity spectral slope at maximum	Anisotropy at maximum	Neutron Monitor Station observing maximum
	Year	Month	Date			Hr	Min†				
55	1997	11	06	18 °S, 63 °W	11	13	15	1.6	−6.4(1)	1.3	Oulu, Finland
56	1998	05	02	15 °S, 15 °W	10	14	05	0.1	∼−6(1)	1.9	Goose Bay, Canada
57	1998	05	06	11 °S, 65 °W	4	09	30	0	∼−6(2)	1.9	Oulu, Finland
58	1998	08	24	35 °N, 09 °E	3	02	05	0	∼−6(2)	2.3	Oulu, Finland
59	2000	07	14	22 °N, 07 °W	43‡	10	55	4.0	−6.1(1),(3)	1.1	Sanae, Antarctica‡
60	2001	04	15	20 °S, 85 °W	117	14	30	5.6	−6.4(1)	1.7	Nain, Canada
61	2001	04	18	23 °S, 117 °W	14	03	15	1.0	−4.7(1)	2.0	Oulu, Finland
62	2001	11	04	06 °N, 18 °W	4‡	18	05	0	∼−6(2)	1.9	Sanae, Antarctica†
63	2001	12	26	08 °N, 54 °W	7	06	15	0	∼−6(2)	2.3	Apatity, Russia
64	2002	08	24	02 °S, 81 °W	4	01	30	0	∼−6(2)	1.6	Oulu, Finland
65	2003	10	28	20 °S, 02 °E	44	11	50	6.5	∼−6(2)	2.9	McMurdo, Antarctica
66	2003	10	29	19 °S, 09 °W	18	22	10	3.0	∼−6(2)	1.9	McMurdo, Antarctica
67	2003	11	02	18 °S, 59 °W	15	17	45	0.5	∼−6(2)	2.0	McMurdo, Antarctica
68	2005	01	17	14 °N, 25 °W	3	11	00	0	∼−6(2)	1.9	Oulu, Finland
69	2005	01	20	14 °N, 61 °W	2649	06	55	11.0	−6.8(4)	4.6	Terre Adelie, Antarctica
70	2006	12	13	06 °S, 23 °W	92	13	05	2.8	−7(5)	3.3	Oulu, Finland

*The cosmic ray community has numbered ground-level enhancements in sequence starting with the first measured event in February 1942

**Percentage increase based on 5-minute time interval at a sea level neutron monitor location in Earth's polar regions where the geomagnetic cutoff rigidity is equal or less than the atmospheric cutoff of approximately 1 GV. The maximum percentage increase is observed at high polar latitude stations. See Moraal and McCracken (2012) for details of the large events having multiple intensity maxima

†The times given are the start of each five-minute interval

‡The Sanae increases have been corrected to sea level values. The altitude of Sanae is 856 meters

(1)Lockwood et al. (2002); (2)Average small GLE differential rigidity spectra; (3)Duldig (2001); (4)Plainaki et al. (2007); (5)Plainaki et al. (2009)

Table 2 Systems directly affected by solar emissions (excluding coronal mass ejections)

System	X-rays	Radio emissions	Solar particles
Communications	X	X	X
Navigation Systems	X	X	X
Spacecraft Electronics			X
Spacecraft Operations	X		X
Space Power Systems			X
Manned Space Missions			X
Commercial Aircraft Operations	X	X	X

weather effects of these higher energy particles with specific emphasis on some of the associated space weather effects that occurred during the three GLEs in October–November 2003 known as the Halloween events.

2 Solar Emissions

Solar emissions are associated with major solar activity. These emissions include X-rays, radio emissions, electrons, and energetic ions (mostly protons). These solar emissions are not unique to GLEs; they occur with all major solar particle events. See Gopalswamy et al. (2012) for a detailed discussion of the solar radio emissions and GLEs. Most GLEs are associated with optically visible bright flares of importance 2 or greater, or impulsive soft X-ray emissions with classifications of M or greater (see footnote 3). Table 2 is a list of some space weather effects together with the solar emission sources.

Shea and Smart (1994) and Smart et al. (2006a) identified a bi-modal distribution of solar proton events which they classified as “interplanetary shock dominated events” and “near-Sun injection events”. For the “interplanetary shock dominated events”, a fast, broad, CME-driven interplanetary shock from activity near the central meridian of the Sun continuously accelerates ions throughout its entire passage from the Sun to Earth. For the lower energy protons (e.g. less than approximately 60 MeV) the initial particle flux observed at Earth may be relatively small, but the magnitude continues to increase as the interplanetary shock approaches Earth.

For the “near-Sun injection events” there is identifiable solar activity, usually on the western hemisphere of the Sun, with an associated fast coronal mass ejection that is typically propagating through the western heliographic longitudes as viewed from Earth. In this type of event, Earth is well connected to the solar active region by the interplanetary magnetic field and the solar protons can arrive at Earth in a prompt time frame. As illustrated in Fig. 3, solar particle intensity observed at Earth from activity on the western hemisphere of the Sun typically has a faster increase and higher magnitude than similar activity from the central meridian or eastern sector of the Sun (Shea and Smart 1995).

There are two primary differences between a GLE and an average solar proton event. One primary difference is the hardness of the particle spectrum. Given two solar proton events from the same location on the Sun with similar solar emissions except for the particle emissions, GLEs will have more protons at higher energies (i.e. harder particle spectrum) than an average solar proton event. The second major difference is the location of the “parent solar activity” on the Sun. Of the 70 GLEs identified between 1942 and 2006, only 17 (24 %)

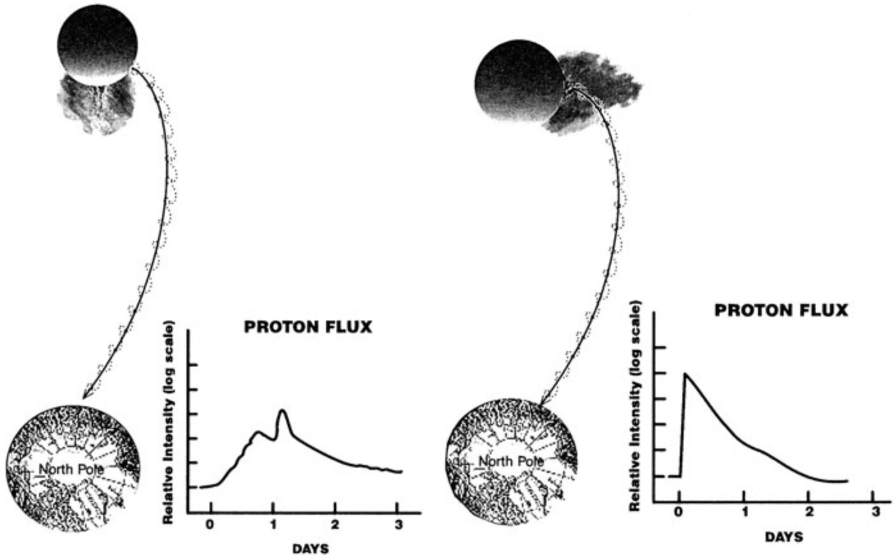

Fig. 3 Conceptual view of two types of solar proton increases typically observed at Earth. *Left side*: Events associated with solar activity near the central meridian of the Sun. *Right side*: Events associated with solar activity on the western side of the Sun. The "additional increase" noted on the left side is the additional flux from the interplanetary shock as it passes by Earth

have been associated with solar activity located between 90° East and 30° West of the Sun-Earth line. Similar to lower energy solar proton events, GLEs associated with solar activity in the region between 90° East and 30° West typically have a slower rate of rise and generally are smaller in magnitude than events associated with solar activity from the more "westerly" portion of the solar disk. GLEs from the western part of the solar disk (or even from solar activity behind the western limb of the Sun) are typically identified by a very rapid rise in proton intensity at Earth as the particles quickly travel along the interplanetary magnetic field lines to Earth. Travelling at velocities close to the speed of light, the highest energy particles can arrive so quickly that it is very difficult to issue an advance warning of an impending high energy solar proton event. These events frequently are highly anisotropic with the anisotropy decreasing over the initial 1–2 hours.

3 Characteristics of Ground-Level Enhancements (GLEs)

3.1 The Spectra of GLEs

The hardness of the particle spectra is the most distinguishing characteristic of solar cosmic ray ground-level events. As an example, GLE 57 on 6 May 1998, a 4 % neutron monitor increase in the polar regions, had a maximum integral $>$10 MeV proton flux increase of 239 protons $(\mathrm{cm}^2\,\mathrm{s\,sr})^{-1}$. This is characteristic of a hard spectra event. In contrast, the solar proton event that commenced on 8 November 2000 having a maximum integral $>$10 MeV proton flux of 14,800 protons $(\mathrm{cm}^2\,\mathrm{s\,sr})^{-1}$ had no discernable increase in any neutron monitor. This was a soft spectra event.

The particle flux may be given in either energy or rigidity. The integral energy flux specifies the flux above a specific energy in units of $(\mathrm{cm}^2\,\mathrm{s\,sr})^{-1}$. The differential energy flux specifies the flux at a specific energy in units of $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{MeV})^{-1}$ or $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV})^{-1}$. When rigidity is used, the integral flux above a specific rigidity is again specified in units of $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr})^{-1}$. The differential rigidity flux specifies the flux at a specific rigidity in units of $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{MV})^{-1}$ or $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GV})^{-1}$. The differential rigidity flux is related to the differential energy flux by

$$dj/dr = (dj/de)(\beta)$$

where dj/dr is the differential rigidity flux, dj/de is the differential energy flux and β is the ratio of the particle speed to the speed of light.

The particle spectra may be given in either energy or rigidity. In this paper we have used differential rigidity spectra. The spectral slopes at 1 GV for the GLEs in solar cycle 23 are included in Table 1. These slopes have been determined at the time of the GLE maximum intensity.

Over the history of solar cosmic ray ground-level event studies, many different forms have been used to specify the energy or rigidity spectrum of the energetic nuclei generating the GLE. The currently preferred form for its simplicity is a power law, either in terms of energy $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV})^{-1}$ or rigidity $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GV})^{-1}$. The original landmark work of Freier and Webber (1963) used an exponential in rigidity. This exponential form is appropriate over several factors of e. It can be used for small GLEs, as in Shea and Smart (1982) for the analysis of GLE 31 (7 May 1978). This exponential form is occasionally still used to describe the initial portion of a GLE spectrum (Vashenyuk et al. 2006). This form generally does not adequately describe the high energy spectra of large GLEs when there is a significant flux of protons with rigidity greater than 10 GV. The power law in rigidity is the currently preferred form to describe the time-evolving GLE spectra and generally works well in the 1–10 GV range.

The differential response function of a polar sea level neutron monitor has a maximum response to a typical GLE particle spectrum at 2.2 GV. Spectra derived from the neutron monitor data are generally quite reliable in the 1 to 8 GV range. Extrapolation of the rigidity power law spectral form to very low rigidities ($<\sim$0.5 GV) or to very high rigidities ($>\sim$10 GV) are less accurate. There is a tendency for the GLE spectra to "bend over" at high rigidities. In the analysis of GLE 42 (29 September 1989; a 373 % increase) Lovell et al. (1998) found it necessary to use a modified power law in rigidity where the slope increases with rigidity to describe the high rigidity portion of the solar ion spectrum as did Bombardieri et al. (2008) in their analysis of GLE 69 (20 January 2005).

McCracken et al. (2008) and Matthiä et al. (2009a) have independently derived the time-evolving spectrum of GLE 69 (20 January 2005). There is some difference about the spectral slope during the initial extremely anisotropic portion of the event, but after the extreme anisotropy, these authors agree that the spectrum softens with time.

The initial spectral slope of the particle flux in a GLE is quite hard and then generally softens as the event progresses. As an example, for GLE 59 on 14 July 2000, the spectral index was 4.9 averaged over the interval 10:35 to 11:00 UT; 5.9 from 11:00 to 12:00 UT; and 6.4 from 12:00 to 13:00 UT (see Fig. 3 of Bieber et al. 2002). These spectral data were derived from the two South Pole neutron monitors (altitude 2820 meters). These high altitude neutron monitors have enhanced sensitivity at $\sim$1–3 GV relative to sea level neutron monitors (Bieber et al. 2007). Assuming the particles are released from the acceleration region at the same time, the difference in velocity means the slower (sub-relativistic particles) will be later in arriving at Earth than the initially observed relativistic particles. Since these relativistic particles remove themselves from the vicinity of Earth faster than the sub-relativistic particles, this effect alone will lead to a softening of the spectral slope of the particles present in the vicinity of Earth. Additional arguments for the softening of the GLE spectra relate to the efficiency of the shock acceleration process as the shock moves into higher regions of the solar corona and into the interplanetary magnetic field.

Tylka and Dietrich (2009) have derived the event-averaged fluence spectral characteristics for the large GLEs. The form of the derived spectra is not a simple function but is a combination of a double power law in rigidity (Band et al. 1993).

Since neutron monitors at different cutoff rigidities are normally used to determine the GLE spectra, it is traditional to give the spectra in terms of rigidity instead of energy. A differential rigidity spectral slope at 1 GV of −4 is extremely hard, a spectral slope of −5 is hard, a spectral slope of −6 is in the average range, and a spectral slope of −7 is soft.

There are several general methods for determining the spectral slope of the particles in a GLE. The oldest method is to compare the increases observed by neutron monitors at different cutoff rigidities. Another method is to compare the responses of two closely spaced neutron monitors with different amounts of shielding. Lockwood et al. (2002) derived the GLE spectra by comparing the response of the sea level Durham, NH neutron monitor with that of the Mt. Washington, NH (1908 m altitude) neutron monitor. Bieber and Evenson (1991), Stoker (1985, 2008) and Vashenyuk et al. (2007) derive the GLE spectra as the event progresses by comparing the response of a "standard" neutron monitor with a co-located "bare unshielded" neutron monitor. A contemporary method is to model the response of all the neutron monitors observing the GLE, derive the anisotropy, and then solve for a spectral slope that reproduces the response of the neutron monitors at different geomagnetic cutoffs. This was the procedure used by Duldig (2001), Duldig et al. (2003), and Bieber et al. (2002) for GLE 59, Bieber et al. (2004) and Vashenyuk et al. (2003) for GLE 60, Plainaki et al. (2007) for GLE 69 and Plainaki et al. (2009) for GLE 70.

It is now recognized that deriving spectral slopes by comparing the increase observed by neutron monitors at different cutoff rigidities can be misleading unless the particle anisotropy is taken into consideration. Spectral slopes derived by this procedure are generally reliable in the later stages of a GLE event when the anisotropy has deceased, but can be quite misleading during the early phase of a GLE. This accounts for some of the differences in spectral slopes reported in the literature, particularly for solar cycle 19 ground-level events

3.2 The Anisotropy of GLEs

The relativistic solar proton flux contained in a GLE is generally anisotropic when measured at Earth. The anisotropy of particles travelling along the interplanetary magnetic field is a function of the number of scattering centers between the Sun and Earth. It is generally accepted that these particles usually have mean free path lengths of $\sim$0.3 AU with a variability of a factor of three within the range of normal expectations. When the interplanetary magnetic conditions are quiet such that the magnetic turbulence is relatively minimal, the interplanetary magnetic field lines will approximate the "idealized Archimedean spiral configuration". Under these conditions, the solar particle flux travelling along the interplanetary magnetic field can be extremely well collimated giving rise to a very anisotropic particle flux distribution about the interplanetary magnetic field lines. In some cases the anisotropy, defined as the ratio of the flux in the forward steradian to the flux averaged over 4π steradians, can be as large as 10 to 1 especially during the onset of a well-connected event propagating though a quiet interplanetary medium. If the interplanetary medium is turbulent, then the particles will undergo many scatterings en route to Earth thereby decreasing the anisotropy.

When this anisotropic flux of high energy solar protons propagating along the interplanetary magnetic field enters Earth's magnetosphere, the result is an uneven illumination of the polar regions even though the geomagnetic cutoff rigidity of these regions is essentially zero. The focusing effect of the geomagnetic field results in an "asymptotic cone of acceptance" for cosmic ray detectors on Earth (McCracken 1962; McCracken et al. 1968; Shea and Smart 1975). In the polar regions, these asymptotic cones of acceptance for the response of neutron monitors are relatively narrow in both latitude and longitude. Each cosmic ray detector has a unique viewing direction in space that is also a function of rigidity; this viewing direction rotates as Earth rotates. If a neutron monitor is "viewing" into the sunward direction of the interplanetary magnetic field, this station will detect the maximum particle increase. If a station is "viewing" in a different direction it will record a smaller increase depending upon the anisotropy (i.e. pitch angle distribution about the interplanetary magnetic field).

Generally the anisotropy is the most extreme during the onset of an event. The longer the duration of an event, the more likely scattering processes will influence particle transport, including reflection of particles downstream of the observer, and the more likely the degree of anisotropy will be reduced. During the onset of a GLE, the characteristic $1/e$ longitudinal flux gradient may initially be of the order of 30 degrees, increasing as scattering reduces the anisotropy.

4 Historical Ground-Level Enhancements

Solar emissions, particularly the events emanating from near the central meridian of the Sun, have been associated with disrupting communications since the mid 19th century. Geomagnetic storms were associated with large sunspot groups or very rare white light solar flares[4] (Hale 1931; Newton 1943; Švestka and Cliver 1992). The Carrington event of September 1859 (a white light solar flare, subsequent severe geomagnetic storm, and low latitude aurora) was well documented (Clauer and Siscoe 2006; Shea and Smart 2006). The geomagnetic disturbance arrived at Earth approximately 17.5 hours after the visual observation of the solar flare (Cliver 2006);[5] this disturbance disrupted telegraph communications world wide (Boteler 2006). This event was also a presumed GLE (Smart et al. 2006b).

In subsequent years, solar researchers noted that a chromospheric brightening observable in the H-alpha absorption line was a positive indicator of solar activity; these brightenings were called eruptions by Hale (1931). According to Cliver (2006), the first use of the term "solar flare" was by Bartels (1932). These solar flares were indicators of massive energy release from the Sun and became useful time markers for the correlation between solar activity and the subsequent sudden commencement of geomagnetic storms (Hale 1931). Routine solar flare observations started in 1932 with the development of the spectrohelioscope (Hale 1929, 1931) and the organization of the IAU solar flare patrol. Beginning in 1934, solar flare patrol results have been regularly reported, initially in the Quarterly Bulletin of Solar Activity of the IAU (Cliver 2006).

The first recorded "space weather effect" associated with a ground-level enhancement was on 28 February 1942 with interference with radar operations in World War II (Lovell 1987). The knowledge that solar activity could produce high energy particles was not published until after the major GLE on 25 July 1946 (Forbush 1946). Using data from ionization

[4] White light solar flares are those visible in normal white light without benefit of special filters. Contemporary solar flare observations are chromospheric brightenings observable in the H-alpha line.

[5] In "normal" space weather events the major geomagnetic storm disruptions occur 1–2 days after the initial solar activity.

chambers, Forbush (1946) and Forbush et al. (1950) associated the sudden increase in cosmic ray intensity with the almost time coincident solar activity and concluded that these high energy particles must have been accelerated at the Sun. Thus the history of the space weather effects resulting from solar protons, particularly ground-level events, is based on less than 70 years of observations.

4.1 GLEs from Solar Central Meridian

In general, GLEs associated with solar activity around the solar central meridian[6] as viewed from Earth tend to be small events. The first GLE associated with activity from near the solar central meridian and recorded by neutron monitors was the small event (∼2 % increase) on 31 August 1956 (McCracken 1959). The 12 November 1960 GLE was relatively unique in that this event is the only case where solar activity near the solar central meridian resulted in a >100 % GLE as measured by neutron monitors. See Lockwood and Shea (1961, 1962), McCracken (1962), and Steljes et al. (1961) for analyses of this event.

The solar activity of August 1972 produced a multiple of flares, CMEs, proton events and interplanetary shocks over a six-day period with resulting effects at Earth that persisted for several days. GLE 24 (4 August 1972) was a unique event inasmuch as the initially presumed solar activity at 8 °E occurred 8 hours before the increases recorded by several neutron monitors. The sea level monitor at McMurdo, Antarctica recorded a five-minute increase of 16.6 % whereas the high altitude South Pole neutron monitor recorded a 5-minute increase of 76 % (Pomerantz and Duggal 1973). Subsequent analysis of this entire period and especially the unusual neutron monitor observations led to the conclusion that this increase was associated with interplanetary shock acceleration of the high energy particles that were in the interplanetary medium between the Sun and Earth at that time (Levy et al. 1976).

The next cases where central meridian solar activity resulted in significant GLEs were on 19 October 1989 in solar cycle 22 and two of the three “Halloween events” in 2003, discussed in Sect. 6. As shown in Table 1, these two “Halloween” GLEs with increases of 44 % and 18 % were relatively small in comparison with the 12 November 1960 GLE when an increase of 135 % was recorded by the neutron monitor at Thule, Greenland.

4.2 Summary of GLEs during Solar Cycles 19–23

In solar cycle 19 (May 1954–October 1964), there have been 10 ground-level events identified.[7] Two of these events were associated with solar activity within 30 degrees of solar central meridian. The largest event observed by neutron monitors to date was on 23 February 1956 (associated with solar activity at 80° West), having a maximum peak increase of 4550 % (15-minute data observed at Leeds, UK, at a geomagnetic cutoff rigidity of 2.15 GV). There were no neutron monitors in the polar regions with a geomagnetic cutoff rigidity <1 GV at that time. For this large event, the flux recorded by the neutron monitors exceeded 100 % for 8.0 hours, and exceeded 10 % for 27 hours. See Meyer et al. (1956) and

[6] We are considering only solar activity between 30 °E and 30 °W as “near solar central meridian”.

[7] Very small GLEs (<5 %) may have been missed during solar cycle 19 as there were no polar neutron monitors before the IGY (1957–1958).

Pfotzer (1958) for the initial analyses of this event. For contemporary modern analyses of this event see Smart and Shea (1990), Belov et al. (2005), or Vashenyuk et al. (2008).

In solar cycle 20 (November 1964–June 1976) there were 13 ground-level events identified. Only one of these events (GLE 24, 4 August 1972) was associated with solar activity within 30 degrees of solar central meridian (see Sect. 4.1). Excluding the event of 4 August 1972, the largest GLE associated with a solar flare (at 49° West) during this cycle was on 24 January 1971, with a maximum increase of 24 % (5-minute data) recorded by the neutron monitor at McMurdo, Antarctica. This event exceeded 10 % for 1.3 hours. See Duggal and Pomerantz (1972) for an analysis of this event.

In solar cycle 21 (July 1976–September 1986) there were 12 ground-level events; however, none were associated with solar activity within 30 degrees of solar central meridian. The largest GLE during this cycle was on 7 May 1978 (associated with solar activity at 72° West), with a maximum increase of 125 % (5-minute data) recorded by the neutron monitor at Apatity, USSR. This event exceeded 100 % for 0.16 hours and exceeded 10 % for 1.1 hours. See Smart et al. (1979) for an analysis of this event. Therefore it is not surprising that the majority of space weather effects during solar cycle 21 were associated with geomagnetic disturbances and particle flux enhancements in the magnetosphere. None of the spacecraft anomalies noted in solar cycle 21 as identified in the Bedingfield et al. (1996) and the Koons et al. (2000) publications were associated with a ground-level enhancement.

In solar cycle 22[8] (October 1986–September 1996), there were 15 ground-level events, three of which occurred between 30 degrees East and 30 degrees West of solar central meridian. Two of these GLEs occurred during episodes of activity when there were multiple solar flares, large X-ray events, fast coronal mass ejections and major geomagnetic disturbances. The largest GLE during this cycle was on 29 September 1989 (associated with solar activity at ∼105° West), with a 373 % (5-minute data) increase recorded by the neutron monitor at Inuvik, Canada. This event exceeded 100 % for 6.0 hours and exceeded 10 % for 12.9 hours. See Swinson and Shea (1990), Smart et al. (1991), Humble et al. (1991), Lovell et al. (1998) and Vashenyuk et al. (2001) for analyses of this event.

In solar cycle 23 (October 1996–December 2008), there were 16 ground-level events. These included the largest peak flux GLE since 1956 although it was a very impulsive, anisotropic short duration event. This large GLE occurred on 20 January 2005 (associated with solar activity at 58° West), with a 2649 % increase recorded by the neutron monitor at Terra Adelie, Antarctica. This event exceeded 100 % for 1.1 hours and exceeded 10 % for 11 hours. See Plainaki et al. (2007), Bombardieri et al. (2008), Bütikofer et al. (2008), McCracken et al. (2008) and Matthiä et al. (2009a) for analyses of this event. This 2649 % increase was recorded for a 5-minute time period; however, when averaged over a 15-minute time period, the increase was 2005 % making the 20 January 2005 GLE less than half the maximum increase recorded by the Leeds neutron monitor during the 23 February 1956 event. During solar cycle 23, there were eight GLEs associated with solar activity between 30 degrees East and 30 degrees West of solar central meridian (see Table 1). Two of these are during the "Halloween 2003" sequence of activity. The increase on 28 October 2003 of 44 % (5-minute data) was the largest GLE associated with solar activity near the central meridian of the Sun since 19 October 1989 which had a comparable increase recorded by polar neutron monitors.

[8]Kahler et al. (2012), provide a table of the GLEs in solar cycle 21–23 containing associated solar and CME data (when available).

Table 3 Major space weather events in solar cycle 22

13 March 1989	Power loss in Quebec, Canada; induced geomagnetic currents	
22–24 March 1991	GOES-7 solar cell degradation	
	GOES-6 and GOES-7 increased single event upsets	
	Power surges and power outages in the eastern USA and Canada	
25 March 1991	Loss of MARECS-1 due to serious damage to its solar panels	
20 January 1994	Anik E-1	Spacecraft charging; temporary interruption of spacecraft operation
	Anik E-2	Spacecraft charging; six month loss of operation
22 February 1994	BS-3A	Spacecraft charging; temporary loss of operation

5 Space Weather Effects on Technological Systems

The term "space weather" in relation to environmental effects on spacecraft and ground-based technological systems became popular in the mid 1980s (Kane 2006). As our technological assets in space increased, so did the awareness of the vulnerability of many of these assets. Major events were well documented by scientists and engineers in addition to being publicized by the general press. Most of the well-known and well-publicized anomalies are those attributed to enhanced electron and proton fluxes in the magnetosphere, geomagnetic storms, and geomagnetically induced currents in electrical power system transmission lines. The well publicized space weather events from 1989 through 1991 are listed in Table 3; none of these events was associated with a ground-level cosmic ray enhancement.

Bedingfield et al. (1996) document more than 100 case histories of spacecraft system failures and other anomalies attributed to the natural space environment from 1974 through 1994 (essentially solar cycles 21 and 22). The NOAA NGDC spacecraft anomaly database[9] lists 5033 anomalies from 22 July 1986 until 6 August 1996 (essentially solar cycle 22). None of the events included in this database are coincident with ground-level enhancements. Using a variety of non-homogeneous anomaly databases covering both solar cycles 21 and 22, Koons et al. (2000) attempted to diagnose the cause of 299 individual spacecraft anomalies. While most of the spacecraft anomalies studied by Koons et al. (2000) were attributed to electrostatic discharges and spacecraft charging, these authors attributed 15 anomalies to single event upsets resulting from galactic cosmic radiation and attributed nine anomalies to single event upsets from solar particle events. In addition there were 41 single event upsets that could not be uniquely attributed to a specific cause. Of these 41 uncategorized single event upsets they felt that most were the result of galactic cosmic ray interactions in semi-conductors with a few probably associated with solar proton events.

The following sections present brief overviews of the different effects that solar particles have on various systems. These are general effects for all major solar proton events including ground-level enhancements. In general the relativistic portion of a solar proton event is relatively short-lived on a time scale of hours in comparison with the duration of MeV protons which can be present for 1–2 days for an isolated event and upwards of a week during a sequence of solar activity associated proton events. The only unique space weather effects that can be attributed to the energy and particles that produce a ground-level enhancement are (1) increased single event upsets, (2) interference with CCD imaging devices, (3) star tracking positioning problems, and (4) increased space radiation for space missions and at aircraft altitudes.

[9] http://www.ngdc.noaa.gov/stp/satellite/anomaly/doc/anom5j.xls.

5.1 Space Weather Effects on Communication and Navigation Systems

Solar X-rays and EUV from solar activity on the visible side of the Sun increase the ionization in the sunlit ionosphere and affect communications. During a major solar X-ray event, high frequency communications on the sunlit side of Earth can be seriously disrupted for the duration of the event. Most X-ray events are relatively short-lived (of the order of an hour); however, major events can last for several hours. This is one reason why aircraft pilots flying in sunlit areas are informed when there is a significant probability that solar activity might produce an X-ray event during their flight that could result in the loss of high frequency communication between the aircraft and the ground. Solar radio noise can also disrupt communications because the magnitude of the radio noise emitted during the solar flare can effectively jam radio frequencies, particularly if the peak flux is greater than 10,000 sfu.[10] During solar cycle 23, incidences of solar radio interference are documented by Gary et al. (2004) and Cerruti et al. (2006). Solar radio noise can also interfere with receiving telemetry and TV transmissions from satellites.

Protons of GeV energies travel to Earth as quickly as 11 minutes if the solar active region is well connected to Earth via the interplanetary magnetic field lines. The difference between the travel time of light from the Sun to Earth—8.3 minutes—and the travel time for relativistic protons is the result of the additional path length traversed as the protons spiral along the interplanetary magnetic field lines. While solar X-rays and radio emissions affect only the sunlit portion of Earth's ionosphere, solar particles affect communications in both sunlit and nighttime polar regions. When the ionosphere is highly ionized, high frequency radio communication may not be possible (see Bailey 1964, for a review on the early work). This phenomenon was called the polar cap blackout in the 1940s and 1950s. The radio frequencies emitted by ionosondes to probe the state of the ionosphere can be completely absorbed, and as a result there is no return signal. After the invention of the riometer (Little and Leinbach 1959), the term "polar cap absorption" was adopted (Reid 1974). More contemporary measurements can determine the degree of attenuation that radio waves from stellar radio sources experience propagating through the ionosphere. This provides a quantitative measure of the degree of the additional polar cap absorption (i.e. PCA events). During a polar cap absorption event there are changes in the height and density of the ionization layers in the polar regions. Even for very low radio frequencies, the normal wave guide that channels the communications is altered such that communication frequencies must be adjusted. Navigation systems that rely on communications may be degraded during both solar X-ray and solar proton events.

5.2 Space Weather Effects on Spacecraft Operations

Spacecraft operations of many types may be compromised by an influx of high energy particles. Energetic particles can penetrate a solid state device, and the energy deposition in the device can generate enough electrons to change the electronic state of the device from "off" to "on". This type of error is called a single event upset or an SEU and is known as a "soft error" since the solid state device continues to operate properly (Bedingfield et al. 1996; Ziegler and Srinivasan 1996; Ziegler 1996). In the extreme case, heavy nuclei may deposit so much energy that the solid state device is irreparably damaged and ceases operation. Some solid state devices are less susceptible to SEUs, and radiation hardening of spacecraft electronics is a significant part of the semi-conductor industry.

[10] The radio astronomy unit "sfu" means solar flux units. One sfu equals $10^{-22}\ \mathrm{W\,m^{-2}\,Hz^{-1}}$ (Castelli et al. 1973; Castelli and Guidice 1976).

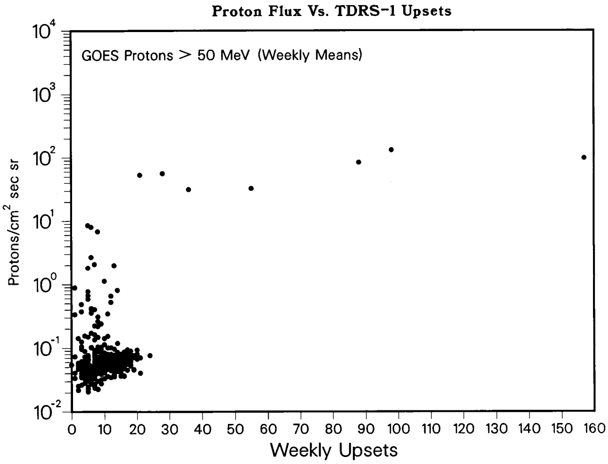

Fig. 4 The number of weekly upsets on the TDRS-1 spacecraft as a function of the weekly mean proton flux >50 MeV recorded by GOES-7. See text for details

Electronics on spacecraft that are not hardened for the space environment are particularly vulnerable to upsets, malfunctions, and even failure during very large solar proton events. As an example, the Fairchild 93L422 chips in the attitude control system on the TDRS-1 spacecraft were highly susceptible to Single Event Upsets (Wilkinson et al. 1991, 2000). The TDRS-1 database[11] archived at the US National Geophysical Data Center consists of the total number of TDRS-1 Single Event Upsets (SEUs) that occurred from April 1983 until December 1993. Shea et al. (1992) found that SEUs in the Fairchild 93L422 chip were most likely to occur when the >50 MeV solar proton flux exceeded 10 particles $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr})^{-1}$. This effect is illustrated in Fig. 4 where the number of SEUs has been plotted as a function of the weekly mean >50 MeV solar proton flux as recorded by the GOES-7 spacecraft. Although this specific threshold effect is a function of the Fairchild 93L422 chip in TDRS-1, it implies that >50 MeV protons have enough energy to penetrate the spacecraft skin and interact with vulnerable electronics. Although the weekly means of the database are not adequate to establish a relationship between individual particle event fluence and the number of SEUs for small or moderate events, it was possible to establish a relationship for the large events where the weekly mean proton flux above 50 MeV exceeded 10 protons $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr})^{-1}$ and corresponding increases in SEUs were recorded. These periods, as shown by the seven points across the top of Fig. 4 were in August, September and October 1989, March and June 1991, and October–November 1992. With the exception of March 1991, all the other periods had one or more ground-level events. The highest numbers of SEUs were recorded during the major ground-level events of September and October 1989 when four GLEs were recorded (Shea and Smart 1993).

During ground-level enhancements, various types of spacecraft sensors and operations may be compromised. These include interference with command and control, the downloading of data, general housekeeping activities, etc. The positioning of spacecraft dependent upon star sensors may be impaired by Cerenkov radiation or additional scintillations in the sensor optics. Electronics with CCD's are likewise affected by solar proton events. Figure 5 illustrates the impact of solar protons on CCD recordings "before" and "during" GLE 59 (14 July 2000).

[11] http://www.ngdc.noaa.gov/stp/satellite/anomaly/doc/tdrs5j.xls.

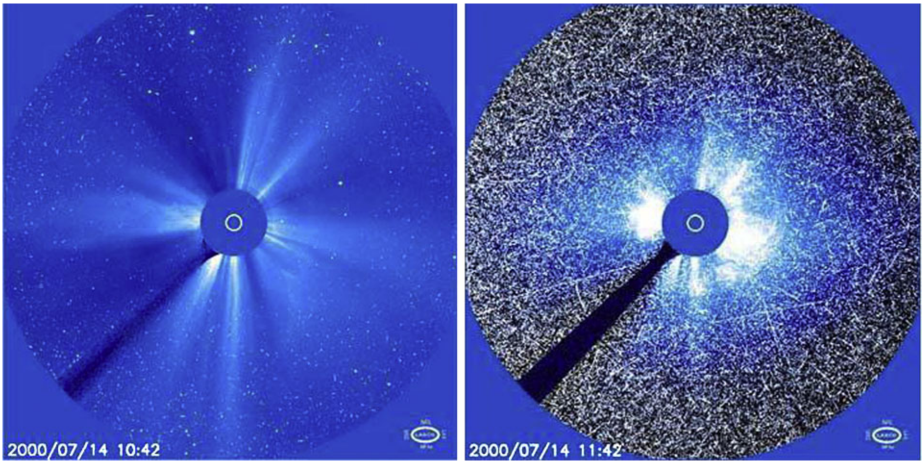

Fig. 5 Solar proton interference on a CCD, 14 July 2000. The *left side* shows the standard pre-event SOHO coronagraph image of the solar corona; the *right side* shows the interference from the solar protons interacting with the CCD semi-conductors. (Courtesy, NASA)

There have been anecdotal reports of cases when data from a spacecraft were lost because a strong X-ray event generated enhanced ionization in the ionosphere which impeded the data flow between the spacecraft and the ground tracking station. Some of these deleterious effects may be mitigated by the reconfiguration of instruments or re-orientation of the spacecraft.

5.3 Space Weather Effects on Space Power Systems

Solar cell arrays are vulnerable to the impact of solar protons. The radiation exposure due to a large solar proton event may be the equivalent of several years of normal radiation effects. While spacecraft are designed to accommodate a gradual decline in solar panel power output over many years of operation, intense high-energy radiation can permanently damage solar panel electronics and cause an accelerated power degradation decreasing the life expectancy of a satellite by several years. During solar cycle 23, the GLE and major solar proton event on 14 July 2000 (GLE 59, a 43 % increase), the power output from the solar array on SOHO was degraded by $\sim$2 % and the power output from the solar array on the WIND spacecraft was degraded by $\sim$1 % (NASA 2004). During solar cycle 22, the Magellan spacecraft experienced reductions in the output of the solar power arrays as a result of the solar proton events in August, September and October 1989.

5.4 Space Weather Effects on Manned Space Missions

Spacecraft crew members are exposed to a constant galactic cosmic radiation environment during an Earth-orbiting mission. As a manned spacecraft circles the globe, the natural cosmic radiation environment in the equatorial regions is less than at mid to higher latitudes as a result of geomagnetic field shielding against cosmic rays. The structure of the International Space Station provides adequate shielding for small solar particle events. During a major solar proton event, the amount of radiation, particularly at higher latitudes may significantly increase for several hours. During any specific mission, if a major solar proton event is forecast, operational personnel must evaluate the probability of this event vs. the potential additional radiation exposure to an astronaut especially if extra vehicular activity is scheduled (NAS 2000; NCRP 2002). The probability of a major solar proton event must be carefully evaluated during missions to the Moon since the Moon's orbit is outside the shielding effect of the geomagnetic field.

5.5 Space Weather Effects on Commercial Aircraft Operations

Radiation exposure is of concern to the general public. Several models have been developed such as EPCARD[12] (Schraube et al. 2000), PCAIRE (Lewis et al. 2005), JISCARD EX (Yasuda et al. 2011; Kataoka et al. 2011), PARMA (Sato et al. 2008), and CARI-6[13] (Friedberg et al. 1999) that predict with reasonable accuracy (typically within 30 %) the galactic cosmic radiation exposure on commercial aircraft routes. Most commercial aircraft flights occur at latitudes where the shielding effect of Earth's magnetic field prevents the solar particles from reaching the aircraft flight paths. As an example the radiation dosimeters carried on the Virgin Atlantic flight from London to Hong Kong on 14 July 2000 (GLE 59) did not detect any additional radiation exposure during this solar cosmic ray ground-level event (Iles et al. 2004).

There has always been concern that additional radiation exposure could be experienced on high flying aircraft such as the Concorde or along polar routes during ground-level events. During the operational lifetime of the Concorde SST, the aircraft did encounter several large GLEs; the observed radiation exposure (Dyer et al. 2003, 2007; Beck et al. 2008; Lantos and Fuller 2003) was well below any of the international radiation safety limits although the Concorde Europe-North America flight routing did not pass through the polar regions where there would be the maximum radiation exposure during these events.

The aircraft radiation exposure concern has led to monitoring programs, particularly in the European Union. As a result of the EU monitoring program (European Commission 1996), the radiation exposure from several GLEs has been documented. There have been calculations of the radiation that might be experienced from a GLE during a transpolar flight (Lantos and Fuller 2003; Dyer et al. 2007; Matthiä et al. 2009a, 2009b; Bütikofer and Flückiger 2011); however, there has not been any active radiation dosimeter measurements made on transpolar commercial flights during a GLE.

Most transpolar commercial flights operate between 35,000–40,000 feet[14] and spend less than 10 hours of flight time in the high polar regions. Copeland and Friedberg (2010) of the US Federal Aviation Administration have computed the maximum 10-hour dose that could be experienced for each of the GLEs during the 23rd solar cycle assuming that the aircraft spent all 10 hours at the zero geomagnetic cutoff value. These "worst case" calculations estimated the maximum radiation for a transpolar route at different altitudes from 30,000 to 50,000 feet. Table 4 presents these calculations which are based on the fluxes observed by the high energy proton detector on the GOES spacecraft (Copeland et al. 2008).[15] In every case the predicted doses at high polar latitudes at standard commercial aircraft altitudes (30,000–40,000 feet), computed by Copeland and Friedberg (2010), are less than the radiation limits

[12] Available at http://www.gsf.de/epcard.

[13] Available at http://www.cami.jccbi.gov/AAM-600/610/600Radio.html.

[14] A flight level of 36,000 feet corresponds to 11 km in altitude and has an overhead atmospheric shielding mass of 217 $\mathrm{gm\,cm^{-2}}$.

[15] Copeland et al. (2008) compute the radiation dose for all the large GLEs that have occurred since 1986.

Table 4 Estimated 10-Hour effective doses (milli Sv) from solar cycle 23 ground-level events at selected altitudes at 0 MV cutoff rigidity

GLE No.	Date	GLE NM increase (percent)	Duration hrs >10 %	Duration hrs >100 %	Total dose (milli Sv) at selected altitudes		
					30,000 (feet)	40,000 (feet)	50,000 (feet)
55	6 Nov 1997	11	1.6	0	0.0151	0.0536	0.1560
56	2 May 1998	10	0.1	0	0.0004	0.0023	0.0089
57	6 May 1998	4	0	0	0.0045	0.0162	0.0470
58	24 Aug 1998	3	0	0	0.0024	0.0090	0.0266
59	14 July 2000	43	4.0	0	0.0413	0.1830	0.6770
60	15 April 2001	117	5.6	0.6	0.0359	0.1250	0.3510
61	18 April 2001	14	1.0	0	0.0082	0.0258	0.0661
62	4 Nov. 2001	4	0	0	0.0118	0.0599	0.3290
63	26 Dec. 2001	7	0	0	0.0036	0.0128	0.0422
64	24 Aug. 2002	4	0	0	0.0009	0.0047	0.0192
65	28 Oct. 2003	44	6.5	0	0.0241	0.1070	0.4470
66	29 Oct. 2003	18	3.0	0	0.0205	0.0644	0.1910
67	2 Nov. 2003	15	0.5	0	0.0078	0.0238	0.0660
68	17 Jan. 2005	3	0	0	0.0009	0.0063	0.0411
69	20 Jan. 2005	2649	11.0	1.1	0.0888	0.3190	0.8920
70	13 Dec. 2006	92	2.8	0	0.0191	0.0690	0.2030

Notes:

1 milli Sv = 1000 micro SV

Radiation exposure regulatory limits vary by country.

US regulatory background limits (NCRP 1995):

General public: 20 milli Sv per year

Embryo fetus: 0.5 milli Sv per month

EU limits (European Commission 1996):

Radiation exposed workers including air crews: 6 milli Sv per year

General public: 1 milli Sv per year

GLE 69 was extraordinarily impulsive with an extreme anisotropy. Matthiä et al. (2009b) compute slightly lower radiation doses for GLE 69 than Copeland et al. (2008). Matthiä et al. (2009b) calculated the exposure time along the polar flight path at low geomagnetic cutoffs while Copeland et al. (2008) assumed the radiation exposure at zero cutoff extended for 10 hours

recommended by the International Commission on Radiological Protection (ICRP 1991, 1997) for aircrew members and the general public. It is extremely misleading to use the maximum intensity of a GLE as an indicator of the potential radiation dose at polar flight altitudes. The key parameter is the number of hours the GLE increase exceeds 100 %.

There were three GLEs in the 23rd solar cycle when there was an active dosimeter on an aircraft flying during the GLE. Figure 6 shows radiation dose rates and associated neutron monitor and high energy solar proton data during GLE 60 (117 % increase on 15 April 2001) on a flight from Prague, Czech Republic to New York City (Spurný and Dachev 2001). Figure 7 shows the additional increase in radiation exposure from this GLE along the Prague to New York City flight path. There were also aircraft radiation dose measurements

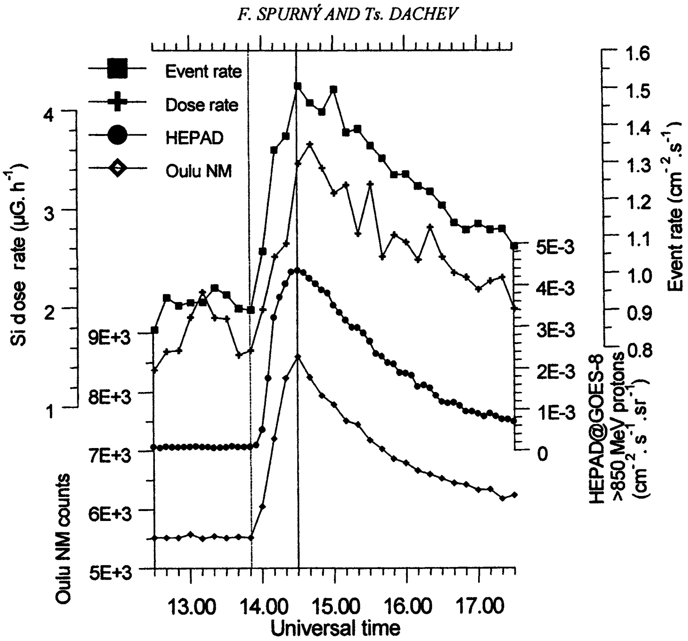

Fig. 6 The dose rate and correlative data on 15 April 2001. The dose rate was measured on an aircraft flight from Prague, Czech Republic to New York City, USA. The *bottom line* is the counting rate of the Oulu, Finland neutron monitor. The *second line from the bottom* is the counting rate of the GOES HEPAD detector which measures >850 MeV protons ($cm^{-2}\,s^{-1}\,sr^{-1}$). The *second line from the top* is the Si dose rate. The *top line* is the event rate in the dosimeter. The onset time of the GLE was 1354 UT. (Used by permission of Ts. Dachev)

during this GLE by Beck et al. (2009) on a flight from Frankfurt, Germany to Dallas/Fort Worth, USA. The radiation dose increase measured by both flights was similar.

6 Space Weather Effects in October and November 2003

In late October and early November 2003 there was an episode of activity on the Sun giving rise to several solar proton events including three GLEs. The magnetic configuration and processes in a solar active region that produce a solar proton event occasionally give rise to multiple events including GLEs from the same solar active region as the region rotates across the solar disk. In solar cycle 23, four solar active regions were each associated with more than one GLE.

The events in October–November 2003 have been called the “Halloween Events” by the solar-terrestrial community, and they provided a plethora of data on multiple disturbances in the solar-terrestrial system. There were three GLEs during this time period: GLE 65 with a 44 % increase, GLE 66 with an 18 % increase and GLE 67 with a 15 % increase as measured by neutron monitors in the polar regions. GLEs 65 and 66 were associated with solar activity close to the central meridian of the Sun and the resulting fast CMEs travelled radially toward Earth. When these CMEs enveloped Earth, the enhanced dense solar plasmas within the coronal mass ejections significantly reduced the intensity of the galactic cosmic radiation observed at Earth. (See Cane (2000) and Kudela et al. (2000) for a review of this

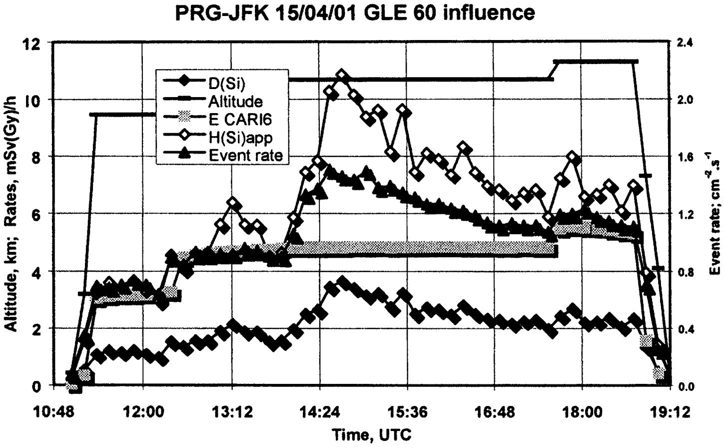

Fig. 7 Flight data and GLE 60 dose rate results from the Prague-New York flight on 15 April 2001 during GLE 60 (a 117 % increase). The *solid line* (*top*) is the aircraft altitude in kilometers. The *bottom line* is the absorbed dose rate (Dose in Si) in micro Gy hr^{-1}. The *grey line* is the predicted CARI-6 cosmic ray equivalent dose rate for the flight path. The *solid triangles* are the dosimeter event rate. The *diamonds* indicate the apparent dose equivalent rate converted from the Si dose rate. (Used by permission of Ts. Dachev)

phenomenon.) The Forbush decrease of ∼20 % following GLE 65 was the largest Forbush decrease of solar cycle 23.

Essentially this sequence of solar-terrestrial events had "something for everyone" and received considerable publicity not only within the scientific community but also from the news media. There were large and fast coronal mass ejections observed, and when the enhanced magnetized plasma in the coronal mass ejections interacted with Earth's magnetosphere, a multitude of space weather disturbances occurred including enhanced solar particles, very large geomagnetic storms,[16] and ionospheric disturbances (Webb and Allen 2004; NOAA 2004).

6.1 Space Weather Effects on Spacecraft

It is difficult to ascertain how many spacecraft were affected by the events in October–November 2003. Operators of commercial satellites are extremely reluctant to share this information for obvious reasons. Therefore most of the information on space weather effects on spacecraft is from government agencies. The Space Science Mission Operations group of NASA prepared an initial report on the operations lessons learned during the Halloween Events; this report was subsequently updated and summarized by Barbieri and Mahnot (2004), and includes information from 34 Earth and Space Science Missions. Of the 34 missions investigated, about 59 % of the spacecraft and about 18 % of the instrument groups experienced some effect from these events.

The effects from solar particles included electronic errors, noisy housekeeping data, solar array degradation, changes to orbit dynamics and increased levels of accumulated radiation

[16]The magnitude of the geomagnetic storm is very dependent upon the orientation of the interplanetary magnetic field embedded in the plasma interacting with the Earth. A large and sustained southward interplanetary magnetic field results in the largest energy transfer into the magnetosphere, significant ring currents flowing in the magnetosphere and the largest geomagnetic storms.

dose. The impact to scientific data included unrecoverable loss of instrument data and reduced quality of recovered data. The NOAA 17 and Mars Odyssey missions permanently lost instruments on 28 October 2003 (Barbieri and Mahnot 2004). In some cases preventative action may have saved some instruments from temporary or permanent effects. These actions included increased monitoring during the events, the placing of instruments into a benign (or safe) mode until the enhanced radiation decreased to acceptable levels, the reorientation of spacecraft to minimize the interference effects, and delays in planned operational procedures. While placing the spacecraft into a safe mode or turning sensitive instruments completely off eliminates the data acquisition from the impacted instruments, this is probably the best way to lower the risk of catastrophic failure to radiation sensitive devices. Once the particle fluence decreases to an acceptable level, the spacecraft and/or affected instruments can be reactivated.

6.2 Space Weather Effects on Aircraft Radiation Exposure

The "Halloween Events" resulted in the rerouting of some transpolar flights since at that time there was no reliable forecast of what the aircraft radiation exposure would be (NOAA 2004). There were some dosimeter measurements on aircraft flights during these "Halloween Events". Beck et al. (2005) acquired dosimeter data on Lufthansa flights between Munich, Germany and Chicago, USA. This monitoring effort extended through the "Halloween Events" time period. GLE 65 (a 44 % increase) commenced about 2 hours into the Munich-Chicago flight on 28 October 2003. The acquired dosimetry data show that the average radiation dose level on this flight was 35 % higher than normal[17] for this flight path (a change from an average of 3.4 microSv hr^{-1} to an average of 5.7 microSv hr^{-1}).[18] The flights on 29 October only encountered fragments of GLE 66 (an 18 % increase). GLE 67 (2 November 2003) did not occur during the Munich-Chicago flight times.

A Mobile Dosimeter Unit (MDU)-Liulin dosimeter (Dachev et al. 2002) was on board a Czech airline flight from Prague, Czech Republic to Sofia, Bulgaria on 25 October 2003 and on board a return flight on 29 October. The first flight was during a period of relatively stable galactic cosmic ray intensity, and the radiation exposure from galactic cosmic radiation was normal. A return flight (Sofia to Prague), on 29 October, occurred between 1328–1519 UT at a time when the galactic cosmic radiation intensity was at a minimum value from the large ($\sim$26 %) Forbush decrease that commenced earlier that day around 0640 UT. In a comparison of the measured radiation dose for the two flights, Spurný et al. (2004) determined that the total radiation dose was reduced by $\sim$25 % for this flight during the Forbush decrease. This flight terminated before the occurrence of GLE 66 (an 18 % increase) that commenced about 2130 UT on 29 October.

Later on 29 October, a Qantas 747 flight, with a different set of active dosimeters, flew from Los Angeles to New York City, USA. The flight commenced at 1750 UT and landed at 2212 UT (Getley 2004). The galactic cosmic ray intensity was at its most depressed value at the onset of the flight, gradually increasing about 5 % until the onset of GLE 66 at 2057 UT. The radiation dose rate of 3.4 microSv hr^{-1} measured before the GLE increased

[17] The radiation exposure due to galactic cosmic radiation at 40,000 feet varies from about 3 microSv hr^{-1} at equatorial latitudes to a range of $\sim$5 to 9 microSv hr^{-1} at polar latitudes depending on the phase of the solar cycle.

[18] The "alert" level for solar particle radiation is a radiation dose rate in excess of 20 microSv hr^{-1} (NCRP 1995).

to 4.7 microSv hr^{-1} during the GLE 66 maximum at 2140 UT.[19] This was a 37 % increase above the pre-event ambient dose rate. This GLE resulted in a total additional increase in radiation dose above the pre-event ambient of about 14 % for the duration of this flight.

This flight occurred during an extreme geomagnetically disturbed period when there was a >20 % decrease in the galactic cosmic ray intensity which was the largest Forbush decrease in the 23rd solar cycle. As a result of the geomagnetic storm, the geomagnetic cutoff rigidities were severely depressed, and the geomagnetic cutoff rigidities in the northern USA were similar to those in the polar regions at the time of the GLE 66 maximum. Since the Forbush decrease had the effect of reducing the total aircraft radiation exposure along this flight path by 23 %, the net result was that the total exposure actually measured during the entire aircraft flight was less than expected from normal galactic cosmic radiation along that flight path (Getley et al. 2005a). In subsequent studies, Getley et al. (2005b) demonstrate that standard aircraft radiation dose models do not include the effects of a major Forbush decrease (e.g. when the galactic cosmic ray intensity is suddenly depressed by more than 10 %).

Since the geomagnetic cutoff rigidity was depressed during both the Czech airline and Qantas flights, the agreement of the amount of reduction of the radiation exposure during the Forbush decrease of 25 % and 23 % respectively is well within the experimental limits considering the different routings.

7 Predicting Ground-Level Enhancements and Their Effects

Currently there are no known methods to predict, from the initial solar observations (white light, UV, X-ray, and radio), if specific solar activity will produce a ground-level enhancement. We know, for example, that when a GLE is in progress there are distinctive gamma ray emissions resulting from the GeV particles interacting with the solar atmosphere (i.e. the 2.2 MeV neutron-capture line and the pion-decay emissions, Ramaty and Mandzhavidze 1994). If this observation is from solar activity to the far eastern portion of the solar disk, it is unlikely that a GLE will be detected at Earth.

The USA Federal Aviation Administration has developed a system to compute the radiation dose during a GLE based on the analysis of the GOES spacecraft high energy solar proton data. While currently intended as a "post event" analysis rather than a real time analysis, this system is capable of predicting the dose rate at various time intervals along transpolar routes and the total dose resulting from the ground-level event (Copeland et al. 2005). In the USA, the NASA Langley Research Center is developing the NAIRAS model to predict the radiation exposure during a GLE along any flight path (Mertens et al. 2010). There is a similar effort in the European Union by EURADOS[20] Working Group 11.

Several groups, individually and collectively, are hopeful that an early warning system of a major solar proton event and other space weather effects can be implemented using GLE observations from neutron monitors. Kuwabara et al. (2006a) have developed a ground-level enhancement alarm system based upon early detection of a ground-level enhancement by a network of eight neutron monitors. In a test of the system using data from ten GLEs in the 23rd solar cycle, the system could have produced alerts for nine of the events. In a

[19] The CARI-6 estimates of the radiation dose at 40,000 feet under normal galactic cosmic radiation for this time period of the solar cycle on this flight path was 5.5 microSv hr^{-1}.

[20] http://www.eurados.org.

comparison of the alert times for these nine events with the GOES 100 MeV or 10 MeV proton observations, the neutron monitor alerts were 10–30 minutes earlier than the alerts from the criteria used in monitoring the satellite measurements.

In a second paper, Kuwabara et al. (2006b) report the development of a real-time system to monitor high-energy cosmic rays for use in space weather forecasting and specification. In addition to the GLE alerts, a careful monitoring of the real-time data from the world-wide network of neutron and muon monitors can be used, in principle, to detect the precursor anisotropy in the cosmic ray flux prior to the arrival of an interplanetary coronal mass ejection at Earth.

Mavromichalaki et al. (2005, 2006) report a procedure and the initial results of using real-time neutron monitor data to forecast ground-level enhancements and, in particular, the arrival of interplanetary disturbances at Earth. In a more recent paper, Mavromichalaki et al. (2011) detailed the implementation of the high-time resolution neutron monitor database that has been designed to provide alerts for GLEs, radiation dose calculations within the atmosphere at several altitudes, and other information for space weather applications. The network includes data from 18 neutron monitors distributed around the world. In a simulation test of the system for ten GLEs between 2001 and 2006, using 1-minute data, the Athens, Greece data processing system successfully produced an alert for nine of the ten events. The GLE alerts produced in this simulation preceded the actual issued alerts from the analysis of the GOES spacecraft data by 4–33 minutes, comparable to the results of Kuwabara et al. (2006a). GLE 70 (13 December 2006) was the first GLE that was successfully detected in real time by the alert capability of the Athens system.

8 Summary

It is now well recognized that solar proton events can adversely affect space and ground-based systems. The high-energy solar proton events known as GLEs have harder spectrum and deposit increased radiation in polar and mid latitude regions. The higher energy particles also significantly impact solar cells and star sensor pointing systems on spacecraft in addition to an overall increase of the radiation environment on spacecraft components and transpolar aircraft flights. None of the GLE's in solar cycle 23 posed a computed radiation risk that would have exceeded the "tolerable" radiation dose as defined by the International Council for Radiation Protection or the European Union.

While there is on-going research to predict these events from solar observables, at the present time the positive identification of a GLE is the arrival of the initial high energy particles detected by cosmic ray ground-based neutron monitors. Nevertheless the analysis of real-time data from a sophisticated, dedicated, and well positioned network of ground-based cosmic ray detectors shows some promise of identifying these events prior to alerts from spacecraft measurements. While only $\sim$15 % of the solar proton events each solar cycle are GLEs, an early warning of these events can alert system operators to make necessary adjustments to vulnerable spacecraft operations and components which may prevent the loss of valuable space assets.

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