JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, XXXXXX, doi:10.1029/2005JA011268, 2005

Introduction to violent Sun-Earth connection events of October–November 2003

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Received 14 June 2005; revised 16 June 2005; accepted 20 June 2005; published XX Month 2005.

[1] The solar-terrestrial events of late October and early November 2003, popularly referred to as the Halloween storms, represent the best observed cases of extreme space weather activity observed to date and have generated research covering multiple aspects of solar eruptions and their space weather effects. In the following article, which serves as an abstract for this collective research, we present highlights taken from 61 of the 74 papers from the *Journal of Geophysical Research*, *Geophysical Research Letters*, and *Space Weather* which are linked under this special issue. (An overview of the 13 associated papers published in *Geophysics Research Letters* is given in the work of Gopalswamy et al. (2005a)).

Citation: Gopalswamy, N., L. Barbieri, E. W. Cliver, G. Lu, S. P. Plunkett, and R. M. Skoug (2005), Introduction to violent Sun-Earth connection events of October–November 2003, *J. Geophys. Res.*, *110*, XXXXXX, doi:10.1029/2005JA011268.

1. Introduction

[2] The violent solar eruptions of October–November 2003 are one of the best observed outbreaks of intense solar activity to date. These events, referred to as Halloween storms, are extreme events in terms of both their source properties at the Sun and their heliospheric consequences. The plasma, particle, and electromagnetic consequences of these events were detected at several locations in the heliosphere thanks to the distributed network of spacecraft. Disturbances associated with two of the October–November 2003 eruptions arrived at Earth in less than a day. Historically, only 13 such "fast transit" events, including the Carrington event of 1 September 1859, have been observed. Remarkably, the two fast transit events in October 2003 occurred on consecutive days, following a delay of over 30 years from the previous such event on 4 August 1972. Several aspects of the Halloween storms, including active region size and potential energy flare occurrence rate and peak intensity, CME speed and energy, shock occurrence rate, SEP occurrence rate and peak intensity, and the geomagnetic storm intensity, displayed extreme behavior [*Gopalswamy et al.*, 2005b].

[3] As expected, this outbreak of strong solar activity resulted in a broad spectrum of space weather impacts. About 59% of the reporting spacecraft and about 18% of the onboard instrument groups were affected by these storms; electronic upsets, housekeeping and science noise, proton degradation to solar arrays, changes to orbit dynamics, high levels of accumulated radiation, and proton heating were observed. Most Earth-orbiting spacecraft were put into safe mode to protect from the particle radiation. Major societal impacts also occurred: ~50,000 people in southern Sweden (Malmoe) experienced a blackout when the oil in a transformer heated up by 10 degrees; surge currents were observed in Swedish pipelines; and several occurrences were noted of degradation and outage of GPS systems. Teams climbing Mount Everest experienced interference on high-frequency radio communication paths.

[4] The solar energetic particle event on 28 October resulted in significant ozone depletion between 40 and 90 km from the ground. A tenfold enhancement in the ionospheric total electron content over the US mainland occurred during 30–31 October. Extraordinary density enhancements in both the magnetosphere and ionosphere coinciding with intervals of southward IMF and high-speed solar wind were observed.

[5] Effects of the eruptions were observed progressively later beyond Earth to the farthest reaches of the heliosphere. At Mars, the MARIE instrument on board the Mars Odyssey mission was completely damaged by particle radiation. The disturbances continued to the orbits of Jupiter and Saturn as detected by Ulysses and Cassini, respectively. Wind, Ulysses, and Cassini radio instruments observed a radio burst resulting from colliding CMEs on 4 November from widely different vantage points. Finally, the disturbances reached Voyager 2 after about 180 days, piled up together as a single merged interaction region (MIR), which led a large depression in cosmic ray intensity, lasting more than 70 days.

[6] In summary, the Halloween 2003 events serve as a useful benchmark of the extreme solar activity and its terrestrial and heliospheric effects [*Gopalswamy et al.*, 2005b; see also *Cliver and Svalgaard*, 2004]. The following provides a synopsis of results obtained by analyzing data acquired during this interval. At this early stage in the data

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0148-0227/05/2005JA011268$09.00

analysis, the emphasis is on the severity of the disturbances and their impacts. Nonetheless, the dynamic range provided by such disturbances has yielded, and continues to yield, insight to their physics.

2. Overview

[7] *Gopalswamy et al.* [2005b] summarize the properties of all the CMEs during this period in comparison with those of all the CMEs observed during SOHO's mission life until the end of 2003. They find that unusually large fraction of fast and wide CMEs and halo CMEs occurred during this period. They report the observation of at least 16 shocks near the Sun using radio data, while eight of them were intercepted by spacecraft along the Sun-Earth line. The CMEs impacting the magnetosphere resulted in intense geomagnetic storms, some of them among the largest ones of solar cycle 23. Very intense SEP events, including three ground level enhancements (GLEs) occurred in association with the CMEs. Gopalswamy et al. find that the extreme CME kinetic energy in the Halloween eruptions is consistent with the largest energy extractable from the huge associated active regions. A plot summarizing solar, interplanetary, and geomagnetic conditions from 19 October to 21 November is given in Figure 1. Note the large number of flares, CMEs in the top three plots. The lull in flare activity during 6–11 November is because the three active regions rotated off to the backside of the Sun. The activity returned when one of the active regions (AR 484) returned as AR 501. The number of CMEs is possibly an underestimate because the SOHO detectors were temporarily saturated by the SEPs during 28–30 October. The bottom two plots show extreme solar wind speeds and superintense geomagnetic storms.

3. Solar Sources

[8] *Woods et al.* [2004] report on total solar irradiance (TSI) measurements in the UV and EUV spectral regimes during this active period. They find that the TSI drops by an unprecedented 0.34% due to the presence of large sunspots on the solar disk. They also report the first definitive detection of a flare in TSI on 28 October.

[9] Using riometer measurements at 20.1 MHz, *Brodrick et al.* [2005] reconstructed the X-ray flare on 4 November which was found to be saturated in the GOES-12 data. The authors suggested that an approximated energy flux of 3.8 mW/m^2 (X38) flare seems to be a more suitable value than the X28 flare estimated from the GOES data. This was the largest soft X-ray flare yet recorded.

4. Disturbance Propagation

[10] *Reiner et al.* [2005] report on a combined analysis of radio and white-light observations of a CME on 2 November using SMEI and Wind/WAVES data. They used these observations to constrain the parameters of a simple kinematic model of CME propagation and to derive the radial speed profile for this CME from the Sun to 1 AU. Their method may provide a framework for more accurate predictions of the arrival of CMEs at 1 AU and thus improved forecasts of space weather events. *Tokumaru et al.* [2005] used interplanetary scintillation measurements to establish unambiguous associations between interplanetary shocks and solar events in the period from 21 October to 8 November. Together, these papers illustrate the importance of tracking disturbances continuously from the Sun to 1 AU in order to establish the link between solar events and in situ measurements of the solar wind near the Earth.

[11] *Jackson et al.* [2005] use a kinematic solar wind density model to perform a three-dimensional (3-D) reconstruction of the 28 October CME from SMEI observations. (For a CME reconstruction for this event based on cosmic ray observations, see *Kuwabara et al.* [2004].) *Jackson et al.* [2005] also derive an estimate for the total mass of this CME in the inner heliosphere. This is the first 3-D reconstruction of a CME from SMEI white light data.

[12] *Wu et al.* [2005] describe the use of a 1.5-D MHD model to study the evolution and interaction of a series of shocks associated with the events from 28 October to 2 November. Their results show the importance of including shock interactions when considering the geomagnetic impacts of successive solar events. *Dryer et al.* [2004] evaluate the application of their "fearless forecasts" to the epoch from 19 October to 20 November. During this period, a total of 19 solar flares were accompanied by metric type II radio bursts, the triggering event for a forecast. The authors compare forecasts of the time of interplanetary shock arrival at Earth obtained by four different (analytic/heuristic, MHD, or kinematic) models. Best results are obtained for the Hakamada-Akasofu-Fry kinematic model with a success rate of 74% (defined as the ratio of hits (forecast arrival time within ±15 hours of observed time) plus correct nulls divided by the total number of forecasts).

5. Solar Energetic Particles (SEPs)

[13] *Mewaldt et al.* [2005] determine that high-energy particle fluence recorded during the late October to early November 2003 period constituted 20% of that observed from 1997–2003. The authors estimate that the energy in the energetic particles in each of the major events during this 2 week interval ranged from ~1 to 25% of the kinetic energy in the associated coronal mass ejections. For each event, they construct energy spectra for H, He, and O over the range from ~0.1 to >100 MeV, and for electrons from 40 keV to 8 MeV. Both the ion and electron spectra can be fitted with double power laws.

[14] *Cohen et al.* [2005] combine SIS and ULEIS data from ACE to construct heavy ion spectra over more than 3 decades of energy for the five large events of October–November 2003. Despite considerable event-to-event variation, two interesting trends are observed: (1) the ratios of abundances at SIS (12–60 MeV) to ULEIS (0.64–0.91 MeV) energies increased in all cases with ionic charge to mass ratio (decreased with nuclear charge); and (2) fluence spectra of O, Ne, Mg, Si, Ca, and Fe within each event could be organized remarkably well by assuming that the positions of spectral breaks for the different elements were governed by their diffusion coefficients. The latter result finds support in the study by *Mewaldt et al.* [2005]. *Cohen et al.* [2005] argue that knowledge of the charge states of heavy ions, and their variation with energy, is

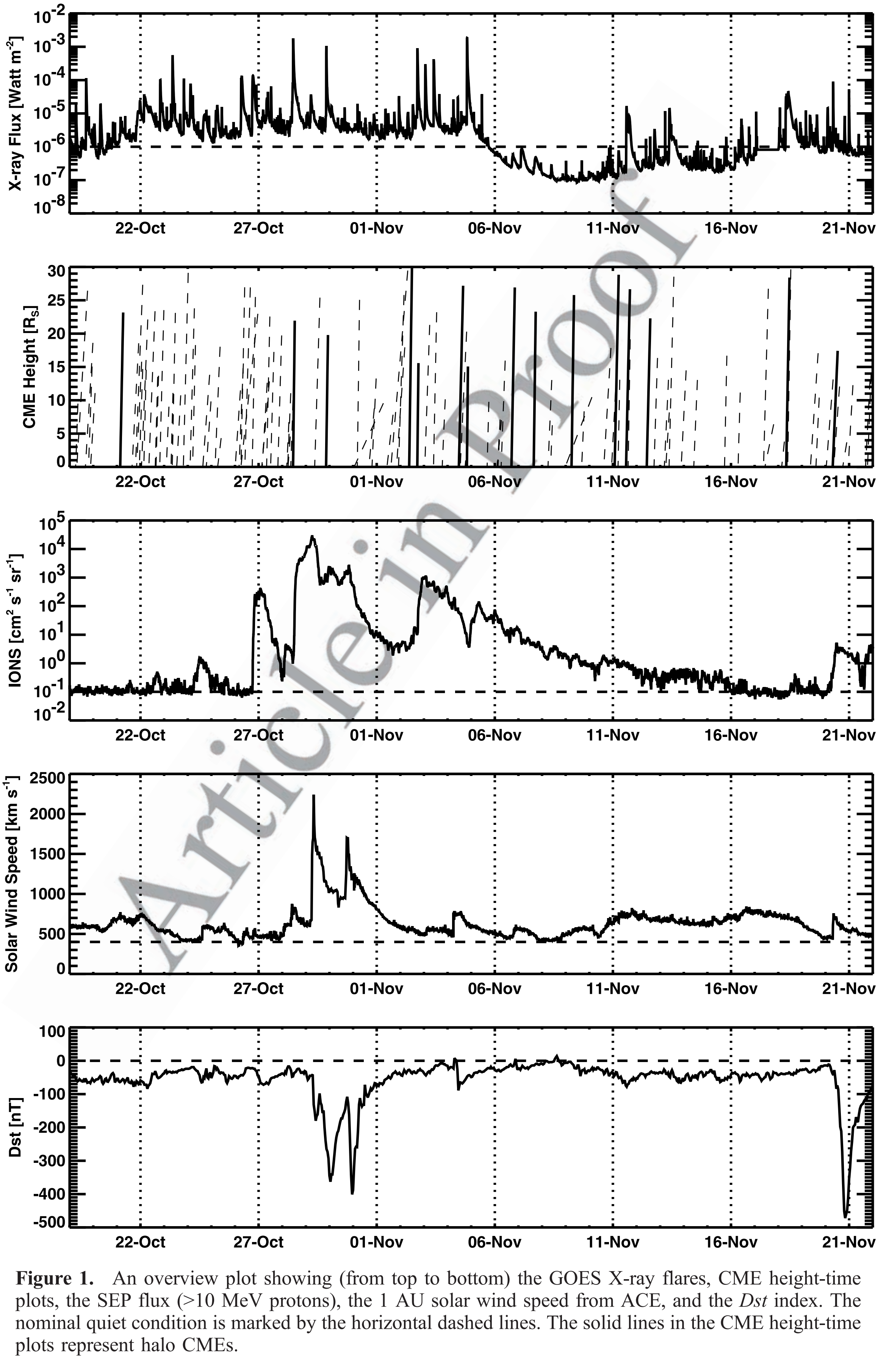

Figure 1. An overview plot showing (from top to bottom) the GOES X-ray flares, CME height-time plots, the SEP flux (>10 MeV protons), the 1 AU solar wind speed from ACE, and the *Dst* index. The nominal quiet condition is marked by the horizontal dashed lines. The solid lines in the CME height-time plots represent halo CMEs.

critical for obtaining further insights into the abundance variations observed in large SEP events.

[15] The current state of understanding of the acceleration and release of SEPs in conjunction with solar eruptions can be seen in a comparison of analyses by *Klassen et al.* [2005] and *Simnett* [2005] of the electron event associated with the X17 flare on 28 October. These authors independently identify phases of SEP injection during this event and suggest acceleration mechanisms for the various phases. From an analysis of radio and electron data, Klassen et al. deduce three phases of particle injection: (1) acceleration of ~30 keV electrons associated with an intense type III radio burst; (2) a delayed impulsive injection of <300 keV electrons and GeV protons; and (3) a further delayed injection of electrons with a hard spectrum at energies above ~100 keV. While the first of these components is attributed to the flare impulsive phase, the origin of the second and third components could lie either in acceleration in a coronal shock or in a reconnection related process in the wake of the CME. In the electron data, Simnett identifies a precursor, a main pulse, and a delayed prolonged component. Simnett attributes the main pulse to a fast CME and the delayed component to the flare. In order to explain the isotropic distribution of the delayed electrons at 1 AU, Simnett postulates that flare electrons are trapped within the CME magnetic structure, from which they leak out over time to fill the inner heliosphere, and are subsequently backscattered from a boundary somewhere in the heliosphere beyond 1 AU.

6. Magnetospheric Impacts

[16] *Looper et al.* [2005; see also *Lopez et al.*, 2004] describe the profound impact that major ICMEs can have on Earth's inner radiation belt. On 29 October 2003, SAMPEX observed that the usual belt of >20 MeV protons around L = 2 almost completely disappeared, to be replaced over the next several months by a belt of >10 MeV electrons that diffused from higher altitudes. Such inner belt disturbances are rare; the only comparable event was the first recognized disturbance of this type, observed by CRRESS in March 1991.

7. Ionospheric and Thermospheric Responses

[17] From an analysis of DMSP ion drift measurements, *Hairston et al.* [2005] concluded that the polar cap electric potential drop was saturated during the 29–31 October superstorm, with the saturation limit at about 260 kV. The ionosphere was severely disturbed during the storms. A highly elevated *F*2 layer was observed by an ionosonde in Kazakhstan, where hm*F*2 (the height of the *F* layer peak electron density) was raised as high as 700 km, along with a 60% decrease of fo*F*2 (the critical frequency of the *F* layer peak electron density) [*Gordienko et al.*, 2005]. In addition, the unusual formation of the *E*, *E*2, and *F*1 layers at night as well as the sporadic *E* layer was also detected. *Sahai et al.* [2005] showed the spread *F* features formed over Brazil and wave-like disturbances in the *F* region height and electron density in both the Brazilian and east Asian longitudinal sectors.

[18] A dramatically decreased plasma density was reported in the southern midlatitude and high-latitude regions following the storm commencement on 29 October [*Yizengaw et al.*, 2005]. The plasma depletion was accompanied by a deep oxygen dayglow depletion observed by IMAGE/FUV, and the region remained depleted for more than 24 hours until 31 October when the second storm began. The depletion of plasma density extended up to ~800 km as measured by DMSP. *Lin et al.* [2005] showed an expanded equatorial ionization anomaly (EIA) up to |40°| latitude during the 29–30 October storm interval, and they attributed it to the strong upward **E** × **B** drift that produces a strong plasma fountain effect. Suppression of the EIA during the storm recovery phase was also found to be associated with the downward drift. A negative storm effect was observed in the Southern Hemisphere, which was corroborated by a reduction in O/N2 ratio in the TIMED/GUVI observations. During the 20–21 November storm, a phenomenon known as a tongue of ionization (TOI) was formed when a continuous stream of cold and dense plasmas is being transported from middle latitudes into the polar region [*Foster et al.*, 2005]. The TIMED/GUVI measured a severe depleted zone of the O/N_2 column density which extended from high latitudes to near the equator at the peak of the storm [*Meier et al.*, 2005].

[19] The storm also caused significant disturbances in the thermosphere. Enhanced meridional and zonal neutral winds of 400 m/s were observed over Scandinavia [*Thuillier et al.*, 2005]. The CHAMP satellite measured a dramatic increase in neutral mass density by 200~300% in the thermosphere at an altitude of ~410 km [*Liu and Lühr*, 2005; *Sutton et al.*, 2005]. The CHAMP measurements displayed a significant hemispheric asymmetry in the neutral density variations, with the Northern Hemisphere showing a greater density increase than the Southern Hemisphere.

[20] The solar forcing was felt on Mars. The Mars Global Survey Magnetometer/Electron Reflector experiment detected strong magnetic field oscillations at and below the oxygen gyrofrequency, an indication that ions of planetary origin are interacting with the solar wind plasmas. *Espley et al.* [2005] speculated that such an interaction may result in a significant atmospheric loss during the passage of large solar storms at Mars.

8. Impact of SEPs on the Earth's Atmosphere

[21] The October–November 2003 solar proton events were ranked as the fourth largest period of SEPs over past 40 years [*Jackman et al.*, 2005]. The highly energetic protons penetrate into the mesosphere and stratosphere where they produce excitations, ionizations, dissociations, and dissociative ionizations. A strong depletion of ozone by 50–70% was observed in the mesosphere and stratosphere in the northern polar cap and a smaller (40%) reduction in the southern lower mesosphere [*Jackman et al.*, 2005; *Rohen et al.*, 2005; *López-Puertas et al.*, 2005a]. The ozone depletion was attributed to the enhanced production of HO_x (H, OH, HO_2) and NO_x (NO and NO_2) by energetic solar protons. Model simulations carried out by *Verronen et al* [2005] showed that an order of magnitude enhancement in HO_x and NO_x in the *D* region could cause a 20–95% reduction in ozone at 40–85 km. The HALOE (Halogen Occultation Experiment) on board the UARS (Upper At-

mospheric Research Satellite) detected an increase of NO_x by more than 20 ppbv over the southern polar region [*Jackman et al.*, 2005], and the MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) instrument on ENVISAT measured an elevated NO_x density of 20–70 ppbv in the Northern Hemisphere and 10–35 ppbv in the Southern Hemisphere in the altitude range of 40–60 km [*López-Puertas et al.*, 2005a]. Enhancement of other ozone-destruction compounds was also measured by MIPAS/ENVISAT, including a 0.2–0.4 ppvb increase of CIO, a more than 0.3 ppvb increase of HOCI, a 2 ppvb increase of HNO_3, a 0.5∼1.2 ppbv increase of N_2O_5, and an increased $CIONO_2$ of 0.4 ppbv [*von Clarmann et al.* 2005; *López-Puertas et al.*, 2005b]. *Gardner et al.* [2005] showed that auroral activity during the storm may also lead to an increased production of N(4S) and N(2D), resulting in enhanced chemical formation of NO in the thermosphere and enhanced 5.3 um emissions such as measured by ENVISAT/MIPAS.

9. Space Weather Forecasting and Its Application

[22] Several of the papers in this special section on the Halloween storms of 2003 provide insight into the value contained in applying current knowledge of space weather.

[23] During the Halloween storms spacecraft in all orbits, LEO, MEO, GEO, HEO, as well as interplanetary missions, were affected by the hostile radiation environment. *Barbieri and Mahmot* [2004] focused on benchmarking the mission effects for this period of atypical severe space weather. Approximately 59% of reporting spacecraft and ∼18% of their instrument groups experienced some effect from solar activity. The benchmark shows that even in one of the most severe space weather events of recent years the effects on and costs to the spacecraft and missions were relatively modest: existing design practices and operations strategies mitigated effects.

[24] *Oler* [2004] provides a study of the prediction performance of five space weather forecast centers for the five strongest interplanetary coronal mass ejections (ICMEs) during this period. The evaluation is particularly intended for the Northeast Power Coordinating Council (NPCC), realizing that accurate time-of-arrival predictions and rapid responses to the upstream detection of strong ICMEs are of paramount importance to such critical infrastructures. Results indicate that the average time-of-arrival error for all forecast centers was 9.26 hours, which is consistent with the guidance errors associated with the leading shock propagation prediction models; overall, the strongest ICME impact events of 29 and 30 October were the most poorly predicted.

[25] In addressing the risk to aircrew and passengers at aircraft altitude from observations made during flights on 29–30 October, *Getley* [2004] presents data from a very scarce occurrence capturing a large unpredictable event with monitoring equipment rarely used on board an aircraft, as well as on an aircraft at a significant latitude and altitude at the time of an event. The author concludes that, while major solar particle events are rare, the increase in equivalent dose rate was ∼37%. Thus solar events can significantly affect the total absorbed dose on longer flights.

10. Conclusion

[26] We have presented an overview of key findings on the size/impact of the Halloween storms of 2003 as presented in AGU journals. This overview is representative, not comprehensive. Space limitations restrict the length of our summary. All of the papers collected electronically in this special series are listed in the reference section. Despite the substantial amount of work that has been completed, the cited references represent only a first installment of observations, analyses, and models of a series of events that provide the definitive example of an outburst of extreme space weather activity.

[27] **Acknowledgments.** Some of these results were presented at the Fall 2003 and Spring 2004 meetings of the American Geophysical Union in special sessions on the October–November 2003 events. We thank S. Yashiro for help with Figure 1. The special sections team acknowledges the efforts by A. Richmond, L. Lanzerotti, and M. Moldwin in making the trijournal special section happen. The effort of NG was supported by NASA/LWS program.

[28] Shadia Rifai Habbal thanks the reviewers for their assistance in evaluating this paper.

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