Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Advances in Space Research 38 (2006) 209–214
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Geomagnetic cutoff rigidities and geomagnetic coordinates appropriate for the Carrington flare Epoch

M.A. Shea *, D.F. Smart

Emeritus, Air Force Research Laboratory (VSBX), Hanscom AFB, 29 Randolph Road, Bedford, MA 01731-3010, USA

Received 24 October 2004; received in revised form 16 February 2005; accepted 10 March 2005

Abstract

Using the trajectory-tracing technique for cosmic rays in the geomagnetic field, vertical cutoff rigidity values for a world grid have been determined for Epoch 1850. These values have been used to derive a world map of iso-rigidity contours that would have been appropriate for the era of the Carrington flare in September 1859. When comparing these iso-rigidity contours with those determined for Epoch 2000, large differences are found, particularly in the Atlantic Ocean region. Geomagnetic cutoff rigidity values and geomagnetic coordinates have been determined for selected mid and low latitude geographic locations for which aurora were sighted during the geomagnetic storms of late August and early September 1859 and compared with the values for those locations calculated for the year 2000. While the geomagnetic latitude differences are relatively small, there are major changes in the vertical cutoff rigidity values for these same locations over this 150-year period. The cutoff differences are attributed to a combination of: (1) the decreasing internal geomagnetic field over the last 150 years and (2) the westward drift of the major features of the geomagnetic field. The relatively small changes in geomagnetic latitude are attributed to the small change in the latitude of the north magnetic pole over this 150-year period. This study emphasizes that while geomagnetic cutoff values are essential for the analysis of high-energy solar proton events, they are not an appropriate parameter for evaluation of the equatorward extent of an auroral display.
Published by Elsevier Ltd on behalf of COSPAR.

Keywords: Carrington event; Epoch 1850; Geomagnetic cutoff rigidities; Geomagnetic coordinates

1. Introduction

The geomagnetic cutoff rigidity is a concept that describes the geomagnetic shielding provided by the earth's magnetic field against the arrival of charged cosmic ray particles from outside the magnetosphere. It is commonly believed that geomagnetic cutoff rigidities are static. This is a misconception as the cutoff rigidity values evolve with changes in the dipole and non-dipole components of the magnetic field. The non-dipole terms contribute about 18% of the total magnetic field. These changes affect the geomagnetic cutoff rigidity and hence the magnitude of the cosmic radiation incident on the atmosphere at a specific location as a function of time. Shea and Smart (1977, 1990, 2004) have shown that contemporary geomagnetic cutoff rigidities are rapidly changing in several areas of the world with increases of the order of 1% per year in the North Atlantic Ocean area and decreases >0.5% per year in the South Atlantic. Furthermore, the changes are non-linear in time. Various analyses have shown that for precise geophysical and cosmic ray measurements the geomagnetic cutoff rigidities must be calculated using a field model appropriate for the time of the measurement (Shea and Smart, 1990, 1997).

At our current point in geological time the earth's magnetic field is rapidly decreasing. As shown in Fig. 1, the magnitude of the dipole term alone has changed by 39% over 400 years (from 1600 to 2000). The changes in the geomagnetic field are so rapid and non-uniform that the IAGA Magnetic Field Working Group (Division V) provides

* Corresponding author. Tel.: +1 603 888 6839; fax: +1 603 888 4733.
E-mail address: sssrc@msn.com (M.A. Shea).

0273-1177/$30 Published by Elsevier Ltd on behalf of COSPAR.
doi:10.1016/j.asr.2005.03.156

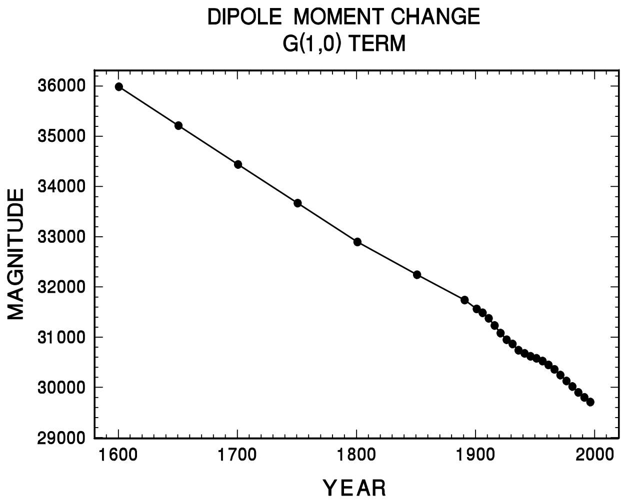

Fig. 1. Change in the magnitude of the main dipole term of the earth's magnetic field over the past 400 years.

updates to the International Geomagnetic Reference Field every five years (Sabaka et al., 1997).[1]

There has been considerable interest in constructing models of the earth's magnetic field in the past (Merrill et al., 1996). Through various international research efforts, models of the earth's magnetic field extending back centuries (Barraclough, 1974, 1978) and even millennia in time (Constable et al., 2000) have been derived, albeit with decreasing confidence in the model accuracy.

In this paper we compare the quiescent vertical cutoff rigidity values calculated for Epoch 1850 with those calculated for Epoch 2000 (Macmillan et al., 2003). From these values we derive iso-rigidity contours that would have been appropriate for a geomagnetically quiet period during the era of the Carrington event in 1859. We also calculated the geomagnetic coordinates for selected "equatorward" locations where aurora were sighted during the period of the Carrington event, and compare those values with the concentric geomagnetic latitudes appropriate for Epoch 2000.

2. Geomagnetic cutoff rigidity calculations

We have calculated a world grid of vertical geomagnetic cutoff rigidities utilizing the International Geomagnetic Reference Field Model for 2000 (Macmillan et al., 2003) and the Barraclough (1974, 1978) geomagnetic field models (restricted to degree and order 5) for 1850. We utilized each of these two magnetic field models with our cosmic ray trajectory-tracing computer program and determined the vertical geomagnetic cutoff rigidity parameters for a world grid every 5° in latitude and 15° in longitude. Details of the trajectory-tracing process for cosmic rays in a model geomagnetic field and the determination of cutoff rigidity values are given by Shea et al. (1965). For the calculations presented here, a quiescent geomagnetic field model was utilized.

Geomagnetic cutoff rigidity contours derived using the 1850 and 2000 geomagnetic field models are illustrated in Figs. 2 and 3. Fig. 4 specifically illustrates the changes in the vertical geomagnetic cutoff rigidity values over this 150-year time interval. The contours are at 1 GV intervals. In these figures, IGRF is a generic abbreviation for the International Geomagnetic Reference Field. We use BGS to designate the 1850 geomagnetic field model developed by the British Geological Survey (Barraclough, 1974, 1978).

The westward drift of the geomagnetic field manifests itself in the cutoff rigidity contours, as there is a northwestward shift of the contours in the Northern Hemisphere Atlantic Ocean area between 1850 and 2000. The position of the north dipole axis has also changed over this time period. In 1850 the North dipole axis was located at

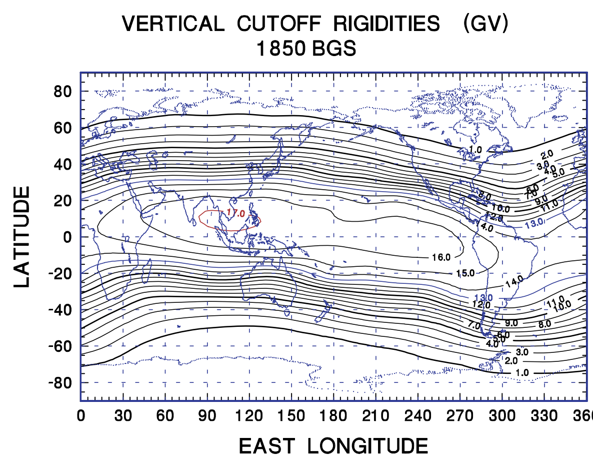

Fig. 2. Vertical cutoff rigidity contours calculated for Epoch 1850. The contours are in 1 GV intervals. BGS designates the model developed by the British Geological Survey (see Barraclough, 1978).

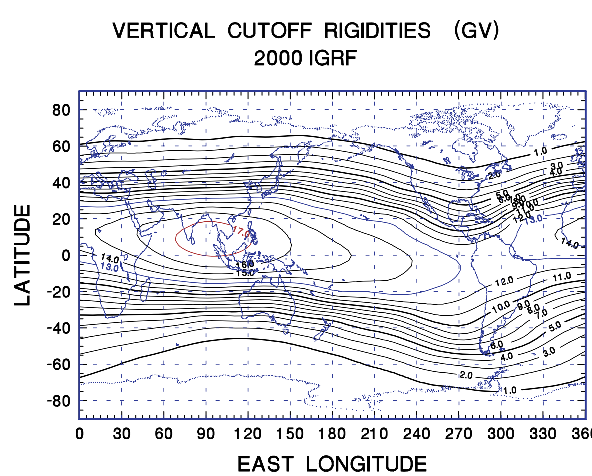

Fig. 3. Vertical cutoff rigidity contours calculated for Epoch 2000. The contours are in 1 GV intervals. IGRF is a generic abbreviation for International Geomagnetic Reference Field.

[1] See Langel et al. (1986) for a discussion of the temporal changes in the geomagnetic field.

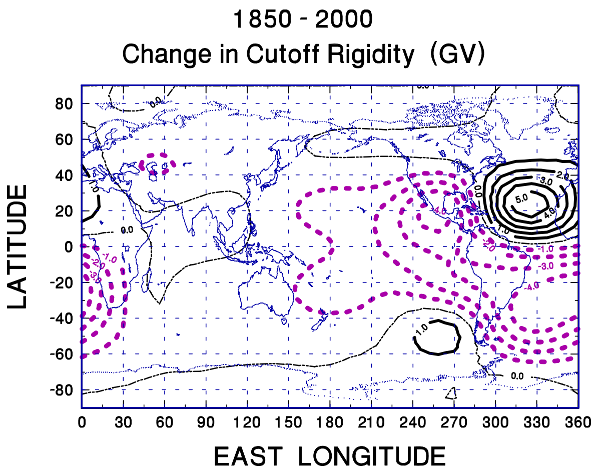

Fig. 4. Illustration of the change in vertical cutoff rigidity between 1850 and 2000. The contours are in 1 GV intervals. The heavy solid lines indicate positive increases in the cutoff rigidity. The heavy dashed lines indicate decreases in the cutoff rigidity. The light line indicates the regions of no change.

78.62° North, 296.40° East; in 2000 it had shifted to 79.54° North, 288.43° East. This represents a drift of ~ 8° West and ~1° North over this 150-year period. The overall decrease in the geomagnetic field is evident from an inspection of the cutoff rigidity contours in the equatorial regions. The maximum cutoff rigidity value over South America in 1850 was between 14 and 15 GV; for 2000 it is less than 13 GV. There are also changes in the cutoff rigidity contours in other regions of the world; however, these are not as noticeable as the changes in the Western Hemisphere.

The two principal factors that contribute to the cutoff rigidity change are the change in the magnitude of the dipole moment (illustrated in Fig. 1) and the relative position of the effective magnetic center with respect to the geocenter. The position of the eccentric dipole from the center of the earth has been changing at the rate of ~0.9 km per year from 1850 to the present. The geomagnetic consequence of this position change has been to accentuate the cutoff rigidity changes over the South American continent while almost compensating for the changes in the Indian-Asian region.

We do not have a magnetospheric model for the 1850 Epoch; the calculation of geomagnetic cutoff values appropriate for a disturbed magnetosphere is beyond the scope of this paper. However, we can make crude estimates of the probable change in magnetic latitude of some of cutoff rigidity contours based on the behavior these contours as a function of the Kp magnetic index in contemporary magnetospheric models (Smart et al., 1999, 2000). The magnetic latitude changes in the cutoff rigidity contours are non-linear with rigidity. In the 1 GV rigidity range, the average magnetic change is approximately 1° per integer unit of Kp. In the 2 GV rigidity range, the average magnetic change is approximately 3/4 of a degree per integer unit of Kp. In the 5 GV rigidity range, the average magnetic change is approximately 1/2 of a degree per integer unit of Kp. In the 10 GV rigidity range, the average magnetic change is approximately 1/3 of a degree per integer unit of Kp.

3. Auroral observations associated with the Carrington event

The appendix to the Catalogues of Geomagnetic Storms (Royal Greenwich Observatory, 1955) lists two major geomagnetic storms recorded at Greenwich during the period of the Carrington event. There was a sudden commencement in the geomagnetic field at 7.5 UT on 28 August. The disturbance was the greatest from 21 UT (28 August) until 10 UT (29 August) with the storm "ending rather abruptly 10 h later". Kimball (1960) reports that an intense aurora was seen in Europe, North America, Australia and at sea; he lists 109 observations of this aurora in Tables II and III in his report.

The second geomagnetic storm began with a sudden commencement geomagnetic disturbance at 4.7 UT on 2 September with the greatest ranges in D and H recorded between 04 and 09 UT on 2 September (Royal Greenwich Observatory, 1955). The Greenwich report further states that at 08 UT there was a wild oscillation in the Z component from a negative value "through a measured range exceeding 1000γ (and perhaps reaching 1500γ to a high positive value at which it remained for about an hour)". Kimball (1960) lists 82 auroral observations, mostly in Europe, North and South America, and at sea. He also states that of the two periods of major auroral sightings, the auroral displays on 2 September were larger and extended to lower (equatorward) latitudes than the aurora on 28/29 August.

4. Discussion

Table 1 contains a list of selected low latitude locations where aurora were sighted during 28 August–3 September 1859. The names of the locations are from the Kimball (1960) report augmented by additional material from Loomis (1859, 1860a,b,c,d); the table is arranged by increasing geographic longitude. The vertical cutoff rigidity values calculated for these specific locations for Epochs 1850 and 2000 are given as well as the geomagnetic coordinates for both Epochs. Fig. 5 is a world map in concentric dipole coordinates appropriate for 1850; the low latitude locations from Table 1 where aurora were observed during the period 28 August–3 September 1859 are identified by solid triangles.

While the vertical cutoff rigidity values for most of these locations have dramatically changed between 1850 and 2000, the changes in concentric geomagnetic latitude are relatively small. This is attributed to the fact that the drift of the geomagnetic pole has not changed appreciably in latitude. Honolulu, Hawaii, at a geomagnetic latitude of 19°, was the closest station to the

Table 1
Low latitude locations for auroral sightings during 28 August–3 September 1859

Location	Geographic latitude	Geographic longitude (E)	Rc (GV) 1850	Rc (GV) 2000	Change (GV)	GM latitude 1850	GM latitude 2000	Change (°)[a]	GM longitude 1850	GM longitude 2000
Athens, Greece	38	24	9.02	8.43	−0.59	38	36	−2	96	103
Wakayama, Japan	34	135	12.46	12.42	−0.04	23	25	2	197	204
Echuca, Australia	−36	145	4.54	3.54	−1.00	−46	−44	−2	214	222
Honolulu, USA	21	202	14.49	12.75	−1.74	20	21	1	261	270
Guanajuato, Mexico	21	258	12.61	8.33	−4.28	30	30	0	318	327
Puebla, Mexico	19	262	12.96	7.81	−5.10	28	28	0	323	331
Corpus Christi, USA	28	263	7.96	5.22	−2.74	37	37	0	322	332
Galveston, USA	29	265	7.07	4.82	−2.25	38	38	0	324	334
San Salvador, El Salvador	14	271	13.61	9.60	−4.01	24	24	0	333	241
Shipboard Observation	13	272	13.78	10.00	−3.78	23	23	0	334	343
Ft. Jefferson, USA	25	277	7.91	5.67	−2.24	36	35	−1	338	347
Key West, USA	25	278	7.75	5.71	−2.04	36	35	−1	339	348
Havana, Cuba	23	278	8.97	6.37	−2.60	34	33	−1	340	348
Barque: Pride of the Sea	28	280	6.10	4.74	−1.36	39	38	−1	341	350
Ship: Southern Cross	−50	280	6.22	6.84	0.62	−39	−40	1	346	353
Bahamas	26	281	6.82	5.42	−1.40	37	36	−1	343	352
Kingston, Jamaica	18	283	10.17	7.37	−2.80	29	28	−1	345	354
Grand Inagua Is., Bahamas	21	285	9.07	7.11	−1.96	32	31	−1	347	356
Concepcion, Chile	−37	287	12.40	9.42	−2.98	−26	−27	1	352	359
Santiago, Chile	−33	289	13.23	10.00	−3.23	−22	−23	1	353	1
Guadeloupe, W.I.	16	298	8.54	11.30	2.76	27	26	−1	2	9
Shipboard Observation	27	314	5.03	10.06	5.03	38	36	−2	20	29
Shipboard Observation	27	325	5.80	11.31	5.51	37	35	−2	32	40
Shipboard Observation	24	325	6.90	12.11	5.21	34	32	−2	32	40
Shipboard Observation	26	331	6.87	12.01	5.14	35	33	−2	39	47
Shipboard Observation	26	333	7.28	12.10	4.82	35	33	−2	41	49
Shipboard Observation	15	336	11.96	13.86	1.90	24	22	−2	42	50

[a] The change in degrees is given in the "equatorward" direction. Thus, a negative value means that the geomagnetic latitude has shifted toward the equator; a positive value means it has shifted "poleward".

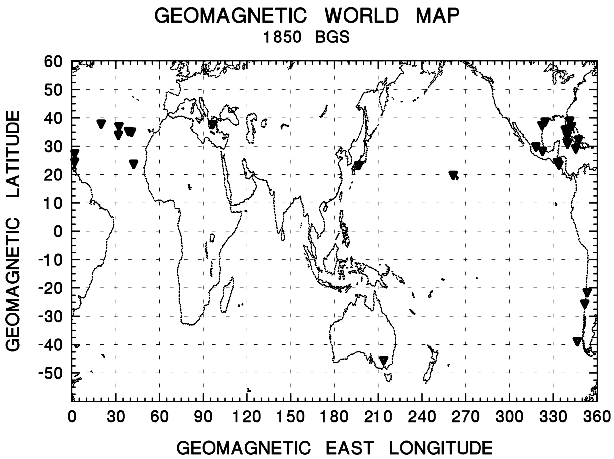

Fig. 5. World map in concentric dipole coordinates appropriate for 1850 calculated using the BGS geomagnetic field coefficients. The locations of the low latitude auroral observations listed in Table 1 are shown by solid triangles.

magnetic equator for which Kimball reports an auroral sighting.[2] An equivalent aurora in 2000 would be visible at slightly lower geographic latitudes in the same region of the world since the geomagnetic latitude of Honolulu has increased (poleward) by 2° over this 150-year period. Changes in the geomagnetic longitude are consistent with the ~8° westward drift of the location of the north dipole axis.

Geomagnetic cutoff rigidity values are used primarily for measurements of the cosmic ray intensity. Other than the major impulsive increase in nitrates in polar ice (McCracken et al., 2001; Shea et al., 2006) it is difficult to determine the geographic distribution of the solar proton flux during the Carrington flare of 1 September. From the work of Smart et al. (2006), we feel that a major solar proton event occurred with perhaps a ground-level enhancement of ~100% in the polar regions. Should such an event occur in the future, the correct geomagnetic cutoff rigidity values would be essential for a worldwide analysis of the high-energy solar proton event. The high-energy component of a solar proton event (i.e., the ground-level event) typically occurs during the first 12 h of the event – well before the arrival of an interplanetary shock associated with solar activity near the central meridian of the sun. Nevertheless, we know from the analysis of recent ground-level events (e.g., Cramp et al., 1997) that geomagnetic cutoff rigidities should be calculated using a magnetospheric field model that contains both the internal field coefficients for the correct Epoch plus the external currents applicable for the geomagnetic activity at the time of the event.

[2] The aurora was also visible from Maui, Hawaii (Loomis, 1860d) approximately 0°26′ closer to the equator than Honolulu, Hawaii.

5. Summary

We have calculated both the vertical cosmic ray cutoff rigidity values and concentric geomagnetic coordinates appropriate for the Carrington flare event in 1859 and for the current Epoch 2000. Even though there has been an approximate 8° change in the longitude of the North dipole axis, there have been only very small changes in the geomagnetic latitudes for selected mid and low latitude locations where aurora were observed in August and September 1859. The latitude of the North dipole axis has drifted only ~1° during the past 150 years. However, the vertical cutoff rigidity values, particularly in the Western Hemisphere, have undergone a very significant change during this time interval.

References

Barraclough, D.R. Spherical harmonic analyses of the geomagnetic field for eight Epochs between 1600 and 1910. Geophys. J., R. Astro. Soc. 36, 497–513, 1974.

Barraclough, D.R. Spherical harmonic models of the geomagnetic fieldGeomagnetic Bulletin, vol. 8. Her Majesty's Stationery Office, London, 1978.

Constable, C.G., Johnson, C.L., Lund, S.P. Global geomagnetic models for the past 3000 years: transient or permanent flux lobes. Phil. Trans, R. Soc., Lond, A 358, 991–1008, 2000.

Cramp, J.L., Duldig, M.L., Flückiger, E.O., Humble, J.E., Shea, M.A., Smart, D.F. The October 22, 1989 solar cosmic ray enhancement: an analysis of the anisotropy and spectral characteristics. J. Geophys. Res. 102, 24,237–24,248, 1997.

Kimball, D.S., A Study of the Aurora of 1859, Scientific Report No. 6, NSF Grant No. Y/22.6/327, University of Alaska report UAG-R109, Fairbanks, Alaska, April 1960.

Langel, R.A., Kerridge, D.R., Barraclough, D.R., Mailn, R.C. Geomagnetic temporal change: 1903–1982. J. Geomag. Geoelectr. 38, 573–597, 1986.

Loomis, E., "The Great Auroral Exhibition of August 28th to September 4th, 1859", The American Journal of Science and Arts, Second Series, vol. XXVIII, No. 84, 285–408, 1859.

Loomis, E., "The Great Auroral Exhibition of August 28th to September 4th, 1859 – (2nd article)", The American Journal of Science and Arts, Second Series, vol. XXIX, No. 85, 92–97, 1860a.

Loomis, E., "The Great Auroral Exhibition of August 28th to September 4th, 1859 – (3rd article)", The American Journal of Science and Arts, Second Series, vol. XXIX, No. 86, 249–265, 1860b.

Loomis, E., "The Great Auroral Exhibition of August 28th to September 4th, 1859 – (4th article)", The American Journal of Science and Arts, Second Series, vol. XXIX, No. 87, 386–399, 1860c.

Loomis, E., "The Great Auroral Exhibition of August 28th to September 4th, 1859; and the Geographical Distribution of Auroras and Thunderstorms – (5th article)", The American Journal of Science and Arts, Second Series, vol. XXX, No. 88, 79–100, 1860d.

Macmillan, S., Maus, S., Bondar, T., Chambodut, A., Golovkov, V., Holme, R., Langlais, B., Lesur, V., Lowes, F., LŸhr, H., Mai, W., Mandea, M., Olsen, N., Rother, M., Sabaka, T., Thomson, A., Wardinski, I., Ninth Generation International Geomagnetic Reference Field Released, EOS, 84 (Issue 46), Transactions, AGU, 503, 2003, and Geophys. J. Int., 155, 1051–1056, 2003.

McCracken, K.G., Dreschhoff, G.A.M., Zeller, E.J., Smart, D.F., Shea, M.A., Solar Cosmic Ray Events for the Period 1561–1994; (1) Identification in Polar Ice, 1561–1950, J. Geophys. Res., 106, 21,585–21,598, 2001.

Merrill, R.T., McElhinny, M.W., McFadden, P.L. The magnetic field of the earth: paleomagnetism, the core and the deep mantle. Academic Press, San Diego, CA, 1996.

Royal Greenwich Observatory Sunspot and geomagnetic storm data derived from the greenwich observations, 1874–1954. Her Majesty's Stationery Office, Norwich, England, 1955.

Sabaka, T.J., Langel, R.L., Baldwin, R.T., Conrad, J.A. The geomagnetic field, 1900–1995, including the large scale fields from magnetospheric sources and NASA candidate models for the 1995 revision of the IGRF. J. Geomag. Geoelectr. 49, 157–206, 1997.

Shea, M.A., Smart, D.F., The Effects of Recent Secular Variations of the Geomagnetic Field on Vertical Cutoff Rigidity Calculations, 15th International Cosmic Ray Conference, Conference Papers, 4, 204–210, 1977.

Shea, M.A., Smart, D.F. The influence of the changing geomagnetic field on cosmic ray measurements. J. Geomag. Geoelectr. 42, 1107–1121, 1990.

Shea, M.A., Smart, D.F., Secular Changes in the Geomagnetic Cutoff Rigidities and their Effect on Cosmic Ray Measurements, 25th International Cosmic Ray Conference, Contributed Papers, 2, 393–396, 1997.

Shea, M.A., Smart, D.F. Preliminary study of cosmic rays, geomagnetic field changes and possible climate changes. Adv. Space Res. 34, 420–426, 2004.

Shea, M.A., Smart, D.F., McCracken, K.G. A study of vertical cutoff rigidities using sixth degree simulations of the geomagnetic field. J. Geophys. Res. 70, 4117–4130, 1965.

Shea, M.A., Smart, D.F., McCracken, K.G., Dreschhoff, G.A.M., Spence, H.E., Solar proton events for 450 years: the Carrington event in perspective. Adv. Space Res. 38, 232–238, 2006.

Smart, D.F., Shea, M.A., Flückiger, E.O., Tylka, A.J., Boberg, P.R., Changes in calculated vertical cutoff rigidities at the altitude of the international space station as a function of geomagnetic activity, in: Proceedings of the 26th International Cosmic Ray Conference. Contributed Papers 7, 337–340, 1999.

Smart, D.F., Shea, M.A., Flückiger, E.O. Magnetospheric models and trajectory computations. Space Sci. Rev. 93, 305–333, 2000.

Smart, D.F., Shea, M.A., McCracken, K.G., The Carrington event: possible solar proton intensity–time profile, Adv. Space Res. 38, 215–225, 2006.