

# The solar-terrestrial event of 23 February 1956

H. Rishbeth<sup>a</sup>, M.A. Shea<sup>b,\*</sup>, D.F. Smart<sup>b</sup>

<sup>a</sup> School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, UK

<sup>b</sup> Emeritus, Air Force Research Laboratory (RVBXS), 29 Randolph Road, Hanscom AFB, Bedford, MA 01731, USA

Received 3 April 2009; received in revised form 24 June 2009; accepted 30 June 2009

## Abstract

The solar flare of 23 February 1956 and the resulting geophysical disturbance ranks as one of the most remarkable solar-terrestrial events of the twentieth century. It sparked many papers and has seldom been equalled. Fifty years after the International Geophysical Year, it seems timely to review the observations of the event from today's perspective, and to draw on the recollections of scientists who were active at the time.

Published by Elsevier Ltd. on behalf of COSPAR.

**Keywords:** 23 February 1956; Solar activity; Solar-terrestrial events; Ground-level enhancements (GLE); Ionosphere; Personal reminiscences

## 1. The solar-terrestrial context of the events of 23 February 1956

The mid-fifties were an interesting time in solar-terrestrial science, culminating in the International Geophysical Year of 1957–1959. After a very low and flat minimum in 1954, solar activity rose sharply in 1955 and reached a high level by February 1956, with a number of major flares around that time. The events of 23 February 1956 were well observed, largely because numerous instruments were operating in readiness for the forthcoming International Geophysical Year. The report by Ellison et al. (1957) of the Geophysical Discussion at the Royal Astronomical Society, held in London a year after the event, gives a synopsis of major features. Other useful sources are the comprehensive account by Bailey (1959) of ionospheric effects of cosmic ray flux enhancements and the ionospheric bibliography compiled by Manning (1960).

To place the 23 February 1956 event in its solar-geophysical context: it occurred in a declining period of the 27-day recurrence pattern of solar activity, in a period of

variable but fairly low geomagnetic activity with the 3-hourly  $Kp$  values varying between 0 and 4+ in the week before the flare. Daily sunspot numbers around this time varied considerably, and fluctuated between 26 and 270 in the few weeks before the flare. Table 1 contains the daily 10.7 cm radio flux, International Sunspot Number and three-hourly  $A_p$  values for 10–29 February 1956. As expected, the flare itself did not affect  $A_p$ .

The reported effects of the flare were strongly influenced by its timing. The optical flare was observed to start at 0331 UT and peaked at 0342 UT – late evening in most of North America, night in western Europe, morning in Russia and India, and midday in the Far East and Australasia.

This retrospect cites a selection of the literature to convey the wide interest taken in the event, but does not claim to be complete. An informal catalogue ‘The solar cosmic ray outburst, 23 February 1956’, embracing solar, cosmic ray, ionospheric and geomagnetic reports and records, was compiled soon after the event by H. Elliot of Imperial College, London, and T. Gold of the Royal Greenwich Observatory at Herstmonceux, Sussex, UK. Being restricted in distribution by the very limited copying techniques of the day, that report may not be widely available and is not included in the formal reference list of the present paper.

\* Corresponding author.

E-mail addresses: [rishbeth@soton.ac.uk](mailto:rishbeth@soton.ac.uk) (H. Rishbeth), [sssrc@msn.com](mailto:sssrc@msn.com) (M.A. Shea).

Table 1

Solar sunspot numbers, 10.7 cm flux (adjusted to 1 AU) and 3-hourly magnetic  $A_p$  values for 15–29 February 1956. Note the subsequent magnetic storm which peaked on 25 February. The flare, which occurred at  $\sim$ 0331 UT on 23 February, did not affect  $A_p$  (denoted by a \* in the table).

Date	Daily sunspot number	10.7-cm Radio flux	3-Hourly $A_p$ values							
1956-02-10	40	119	0	4	4	5	3	3	5	5
1956-02-11	56	131	27	15	6	7	18	12	39	39
1956-02-12	80	151	48	39	56	39	15	7	7	15
1956-02-13	90	160	7	6	18	18	12	6	5	6
1956-02-14	142	182	4	6	5	6	3	4	0	2
1956-02-15	168	215	2	0	6	7	4	3	6	9
1956-02-16	224	236	9	32	15	12	18	22	12	9
1956-02-17	237	244	7	7	9	9	3	6	3	0
1956-02-18	270	247	0	7	5	9	3	5	5	2
1956-02-19	246	244	32	9	15	32	22	9	9	9
1956-02-20	260	240	3	3	4	4	18	7	3	5
1956-02-21	208	233	3	5	4	5	7	7	18	6
1956-02-22	186	217	27	27	15	32	18	15	5	4
1956-02-23	177	201	5	*2	4	6	7	18	7	4
1956-02-24	156	176	4	3	3	12	9	9	5	9
1956-02-25	149	–	3	80	236	154	111	111	111	18
1956-02-26	140	152	18	9	15	39	27	4	18	12
1956-02-27	125	140	27	18	27	6	5	6	48	27
1956-02-28	132	141	39	56	9	15	7	15	27	27
1956-02-29	132	155	56	48	48	32	27	48	27	39

Sixteen months later, the official start of the IGY on 1 July 1957 was heralded by the severe magnetic storms of 30 June and 2 July 1957, both with geomagnetic activity values of  $K_p$  8. Unusually, these events caught the attention of the popular press and public. Some of the popular press appeared to suggest that scientists had arranged the disturbances, which at least provided good publicity for the IGY! The highest values of daily sunspot number (309) and solar 10.7 cm flux (320) in solar cycle 19 occurred much later on 22 January 1959. Geomagnetically, the years 1958–1959 were quieter than 1957 and 1960, the years of peak activity in this cycle. This pattern of greatest magnetic activity during the rise and the fall of a cycle, rather than at the peak of sunspot number, has been observed in other cycles also (Storini et al., 2008).

## 2. The solar active region

McMath Region 3400 at Carrington longitude  $180^\circ$  crossed the central meridian on 17 February 1956. It extended over  $60^\circ$  in solar longitude (Part III of Švestka and Simon, 1975) and was an extremely complex region, as reflected by the sudden increase in sunspot numbers from 13 to 18 February (see Table 1). Fig. 1 is a Fraunhofer Solar Map for 17 February when Region 3400 was at the central meridian of the sun. Sunspot groups are classified according to the Zurich scale. They are represented by circles according to their size; small for types A, B, and J, medium for C, D, G, H, and big circles for E and F. The large solid circle labelled F95 represents a large sunspot group, size F, with 94 spots contained in the group. The circle labelled G20 represents a medium sunspot group containing 20 spots. Fig. 2 is a Fraunhofer Solar Map for 23 February when region 3400 was positioned near  $80^\circ$  West of the

sun-earth line. Two large sunspot regions were identified: E with 27 spots and F with 24 spots. Details of sunspot regions close to the solar limb are difficult to discern because of foreshortening so the number of spots in each region may have been underestimated. (Information on the Fraunhofer maps is available at [ftp://ftp.ngdc.noaa.gov/STP/SOLAR\\_DATA/SOLAR\\_IMAGES/Fraunhofer/](ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_IMAGES/Fraunhofer/).)

The large range of solar longitudes encompassed by this region and the close proximity of this region to the solar limb has also made it difficult to identify the exact location of the visual flare with reports of the flare location covering  $11^\circ$  of solar longitude.

An importance 3 solar flare at N23, W80<sup>1</sup> in McMath region 3400 was observed on 23 February 1956. The H $\alpha$  onset time is listed as  $\leq$ 0334 UT with maximum at 0342 UT (Švestka and Simon, 1975). This flare was also visible in white light (Notuki et al., 1956; Neidig and Cliver, 1983). An importance 3+ short-wave fadeout started at 0330 UT and continued until 0610 UT. The onset of radio emissions was 0334 UT at 3.7 GHz and 0335 UT at

<sup>1</sup> The location of the flare and the onset time are frequently given with different values than cited here. The principle list of solar flare observations used in 1956 was in the *Quarterly Bulletin on Solar Activity* (1956). That reference cites three observations for this event: Mitake, Japan with onset time of 0334 UT and location  $25^\circ\text{N}$ ,  $85^\circ\text{W}$ ; Kodaikanal, India with onset time  $<$ 0335 UT and location  $23^\circ\text{N}$ ,  $80^\circ\text{W}$ ; and Tashkent, USSR with onset  $<$ 0429 UT and location  $20^\circ\text{N}$ ,  $76^\circ\text{W}$ . In addition, records provided by the Tokyo Astronomical Observatory give an onset time of  $0331 \pm 1$  UT with a maximum at 0342 UT; the coordinates listed were  $23^\circ\text{N}$ ,  $74^\circ\text{W}$ . The Tokyo Astronomical Observatory observations were not included in the *Quarterly Bulletin on Solar Activity* (1956). Other references list the flare at  $\leq$ 0334 UT with coordinates at  $23^\circ\text{N}$ ,  $80^\circ\text{W}$  (Švestka and Simon, 1975) which essentially is an average of the three locations given in the *Quarterly Bulletin*.

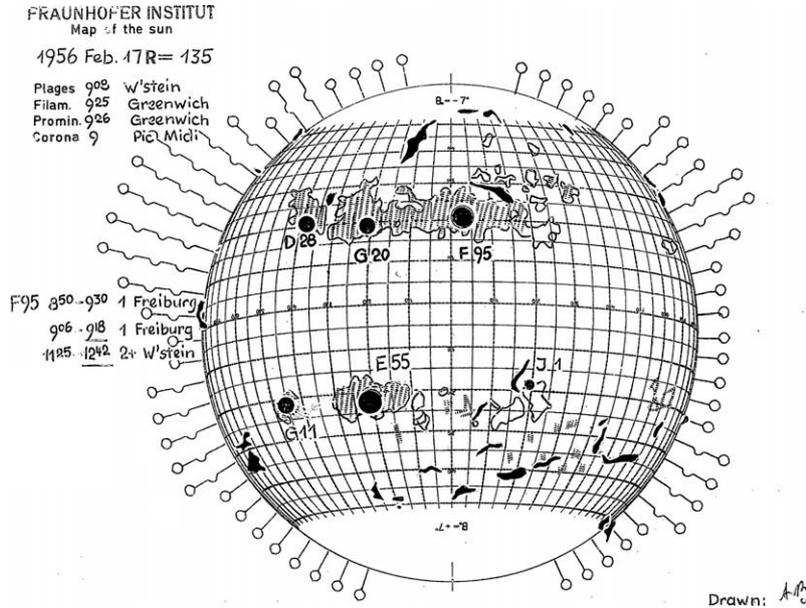


Fig. 1. Fraunhofer plot for 17 February 1956.

200 MHz; the Nagoya, Japan 3.7 GHz radiometer was the highest frequency instrument on patrol during the time of this flare (Neidig and Cliver, 1983). Type IV radio emission was also reported (Švestka and Simon, 1975 and references therein).

In the sunlit hemisphere, the induced ionospheric currents gave rise to a magnetic crochet of the type characteristically associated with major solar flares. There followed two days of magnetic calm, mostly with  $A_p < 10$  (Table 1), with little auroral activity until the storm sudden commencement (SSC) around 0306 UT on 25 February (Mayaud, 1973).

Bailey (1957, 1959) used the opportunity presented by the flare to give detailed accounts of the penetration of energetic electrons, protons and helium ions into the earth's atmosphere. His plot of penetration heights at vertical incidence as a function of particle velocity and rigidity, shown in Fig. 3 of Bailey (1959), has been widely used.

### 3. Solar cosmic ray event

While the first two observations of solar cosmic ray increases occurred in 1942, it was not until the increase of 25 July 1946 that Forbush published his observations of all

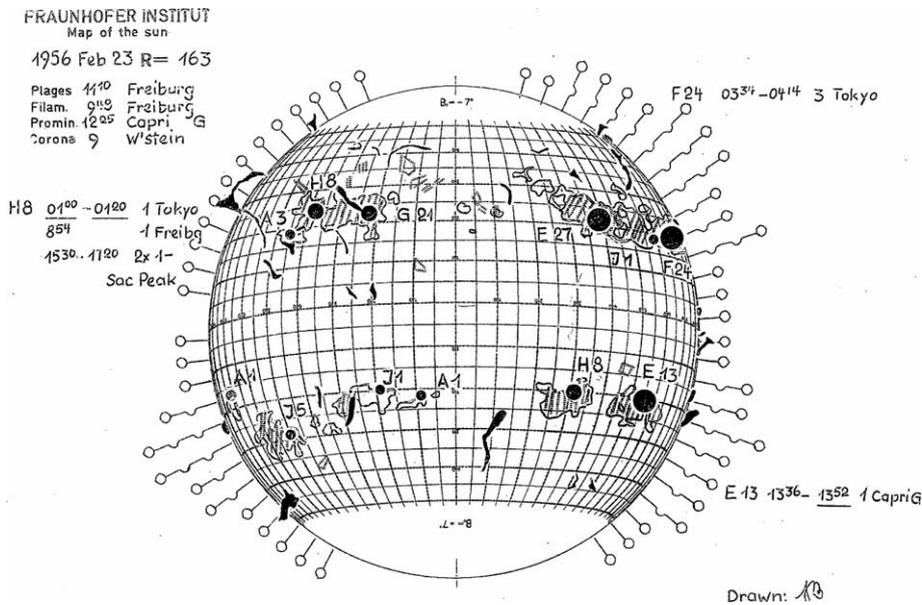


Fig. 2. Fraunhofer plot for 23 February 1956.

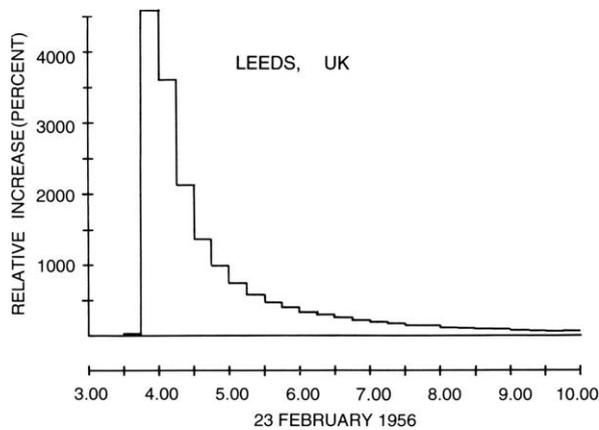


Fig. 3. Solar cosmic ray event recorded at 15-min intervals by the IGY-type neutron monitor at Leeds, UK.

three events as recorded by his ionization chambers (Forbush, 1946). At that time he ascribed the increases as being associated with solar flares. Another increase in November 1949 was recorded by both the Forbush ionization chambers and a prototype neutron monitor being operated at the University of Manchester, UK (Adams, 1950; Forbush et al., 1950). Ionization chambers respond to a nuclear cascade in the atmosphere generated by an influx of energetic protons greater than about 4 GeV at the top of the atmosphere. The newly developed neutron monitor could respond to lower energy protons at the top of the atmosphere, with the limitations being the geomagnetic cut-off rigidity at the observing site or, at sea level locations in the polar regions the limitation is about 450 MeV which is the result of the atmospheric mass above the station.

With plans being made for the International Geophysical Year, the IGY neutron monitor as designed by Simpson

(1957) and the continued operation of the existing ionization chambers were the instruments of choice to monitor the cosmic radiation throughout the IGY. While the work of Forbush and colleagues had shown that the sun could produce a sudden influx of solar protons that would be recorded as sudden increases on the background cosmic radiation intensity, the organizers of the IGY felt that these instances were so rare (only four events between 1935 and 1955) that bi-hourly counting rates (i.e. every 2 h) of the galactic cosmic ray intensity would be sufficient for any correlative studies being undertaken during the IGY. While bi-hourly data was the recommended recording interval for IGY reporting, several scientists had the foresight to install recording equipment that would permit the tabulation of the cosmic ray intensity for shorter time intervals – a fortuitous decision in retrospect.

At the time of the 23 February 1956 solar cosmic ray event there were 17 neutron monitors known to have been in operation as listed in Table 2. In some cases, routine monitoring had not commenced; it was by chance that the monitor was in trial operation during this event. In addition to the neutron monitors, ionization chambers and muon detectors were also in operation.

The onset of the high energy solar proton event recorded by several cosmic ray detectors was  $0345 \pm 05$  UT. The Leeds, UK neutron monitor recorded the highest increase in cosmic ray intensity,  $(4581 \pm 12\%)$ , in the 15-min interval 0345–0400 UT as shown in Fig. 3. Located near 0400 LT, this monitor would have been in a most favourable position for recording a large increase as the Leeds asymptotic cone (McCracken, 1962a, 1962b; McCracken et al., 1965) would sweep across the nominal location of the interplanetary magnetic field line from the sun to the earth. Of course, at that time, the interplanetary magnetic field had

Table 2  
Neutron monitors known to be in operation in February, 1956.

Station Name	Geographic latitude	Geographic longitude (E)	Altitude (m)	Vertical cut-off rigidity (GV) Epoch 1955
Albuquerque, USA	35.03	253.38	1575	4.48
Berkeley, USA	37.86	237.70	70	4.55
Chicago, USA	41.83	272.33	200	1.71
Climax, USA	39.37	253.82	3400	3.06
Durham, USA	41.10	289.17	0	1.38
Göttingen, Germany	51.52	9.93	273	2.94
Huancayo, Peru	−12.03	284.67	3400	13.44
Leeds, UK	53.83	358.42	100	2.15
Mexico City, Mexico	19.33	260.82	2274	9.45
Mt. Norikura, Japan	36.11	137.55	2770	11.35
Mt. Washington, USA	44.30	288.70	1909	1.25
Ottawa, Canada	45.40	284.40	57	1.08
Ottawa, Canada	45.44	284.32	101	1.08
Uppsala, Sweden	59.85	17.58	0	1.39
Sacramento Peak, USA	32.72	254.25	3000	5.10
Weissenau, Germany	47.80	9.50	427	4.18
USS Arneb	−41.28	174.77	0	3.43

Notes. (1) The USS Arneb was located in the Wellington, New Zealand harbor at that time; (2) several stations have “dual” names which can be confusing when researching the original scientific articles. For example, the names of Stockholm and Uppsala, Sweden have both been used for data from the Uppsala neutron monitor. It is not known if this neutron monitor was in Stockholm prior to operation at Uppsala; (3) Appendix A of Shea and Smart (2000) contains additional details on the location and operational dates for neutron monitors.

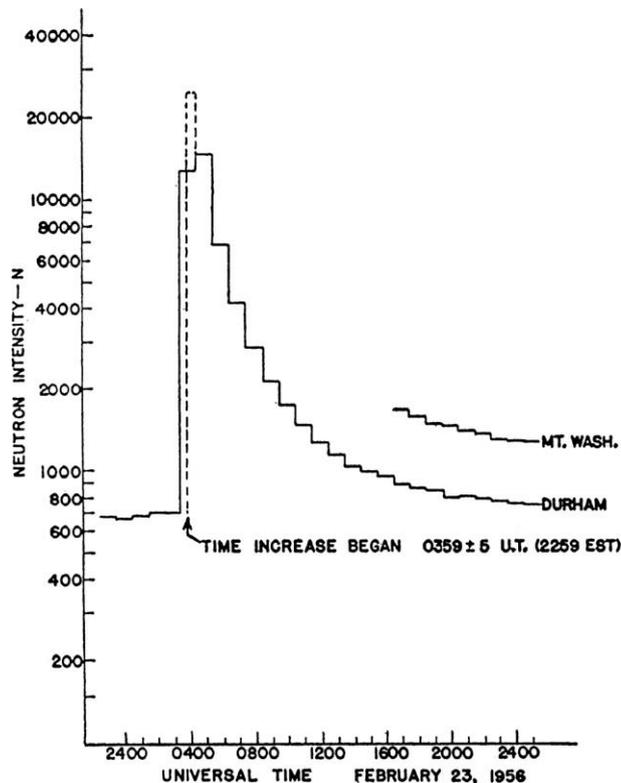


Fig. 4. Solar cosmic ray event recorded hourly by the IGY-type neutron monitors at Durham, NH and Mount Washington, NH, USA. The dashed line indicates the probable reconstructed onset and maximum profile at Durham, NH (adapted from Lockwood et al. (1956)).

not been discovered, and the concept of particle anisotropy was not known.

An interesting side note to this increase is the large number of detectors that were shut down during the event since the “run-away clicking” of the various recording devices alarmed individuals who were in close proximity to the detectors at the time of the event and who assumed that the detectors were malfunctioning (see Appendix). An example of the loss of critical data is shown in Fig. 4 with missing data from the Mount Washington neutron monitor until ~1600 UT. It is noted that a similar situation occurred with the Manchester, UK prototype neutron monitor during the 19 November 1949 solar proton event (Adams, 1950).

The Chicago, USA neutron monitor, located at approximately the same geomagnetic cutoff rigidity as the Leeds monitor<sup>2</sup> recorded a much smaller increase than the Leeds monitor as shown in Fig. 5. Scientists on both sides of the Atlantic Ocean prepared their papers initially using data from the stations in their immediate areas. Without the knowledge of the worldwide aspects of this increase and the anisotropic nature of this event, two different spectra

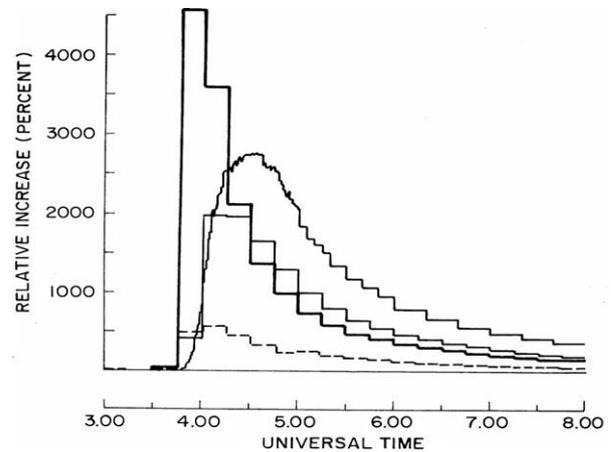


Fig. 5. Neutron monitor observations of the 23 February 1956 high energy solar proton event. The maximum increases are: Leeds, UK (4581% as indicated by the heavy line); Ottawa, Canada (2802%); Chicago, USA (1976% as indicated by the light line); and the USS ARNEB at Wellington Harbor, New Zealand (575% as indicated by the dashed line).

were derived:  $-4$  based on an interpretation of data recorded in Europe (Pfozter, 1958), and  $-6$  to  $-7$  based on data from the American continents (Meyer et al., 1956). Unfortunately these two values became “cast in concrete” in future analyses of ground-level events (GLEs) over the next several decades. Using the method of analysis that employs asymptotic directions of approach and the neutron monitor yield function, plus contemporary (at that time) pitch angle distribution functions, Smart and Shea (1990) derived an initial differential rigidity spectral exponent of  $-3.5$  at the event onset that evolved to  $-4$  after the event maximum. As mentioned below, this event continues to be extensively studied with other evaluations and details of the particle spectrum being derived depending upon the analyses techniques employed. As an example, Belov et al. (2005) derived the spectral evolution of this event and concluded that the spectral exponent was approximately  $-3.5$  at the maximum, softening to about  $-5$  later in the event.

While the magnitude of this event was unprecedented, equally remarkable was the high energy of the particles impinging at the top of the atmosphere producing responses in the earth’s equatorial regions. Increases of 115% were recorded at Mexico City, Mexico and 26% at Huancayo, Peru. While both stations are well above sea level, these measurements indicate that particles in excess of 14 GV were present. Muon telescopes in Kodaikanal and Trivandrum, India recorded increases of  $4.8 \pm 1.6\%$  and  $4.6 \pm 1.6\%$ , respectively (Dorman, 1957). The vertical cutoff rigidities for these two stations were 17.47 and 17.45 GV (Epoch 1955). The ground-level event of 29 September 1989 is the only event since 1956 with substantial increases in the equatorial regions. The maximum increases for sea level, high latitude stations for the 29 September 1989 event were of the order of 400% (Lovell et al., 1998), an order of magnitude lower than the 4581% increase for the 23 February 1956 event.

<sup>2</sup> The effective vertical cutoff rigidity for Leeds was 2.15 GV; for Chicago, 1.71 GV using a 1955 Epoch for the geomagnetic field (see Shea and Smart, 2001).

In 2002 data from 12 neutron monitors for the 23 February 1956 GLE, assembled in the standard GLE data format (Shea et al., 1985, 1987), were deposited in NASA's NSSDC. It is doubtful that the original data for the remaining neutron monitor stations have been preserved. Dorman (1957) published graphs of many of these increases. Although the graphs are continuous lines representing the “possible shape” of the increase over time, with considerable foresight Dorman also included horizontal lines in these graphs indicating the values recorded over specific time intervals. With modern techniques these graphs can be digitized and the appropriate increases can be determined within the statistical limitations of the graphs.

#### 4. Early effects in the ionosphere

The immediate ionospheric effect of the flare was a massive sudden ionospheric disturbance (SID) in the sunlit hemisphere, of the type described by Dellinger (1937), caused by the greatly enhanced ionization in the ionospheric D region below 90 km and to some extent in the overlying E and F regions, which as previously mentioned caused a magnetic crochet, observed for example at Kodaikanal and Singapore. Accurate measurement of the ionospheric changes is very difficult, particularly in the F region, as the greatly increased radio-wave absorption produced by the D region enhancement severely disrupts measurements by ionosondes and other instruments. As ionosondes cannot receive echoes from above the F2 peak, fadeouts and cosmic noise decreases provided the only information (and that very indirect) about flare effects above the F2 peak that was available at the time and indeed for some years later.

During the flare, radio waves traversing the D region suffered a short-wave fadeout, bringing a short-lived but severe disruption of communications. Radio transmissions and cosmic radio noise at frequencies around 25–30 MHz, that easily penetrated the enhanced D region, were attenuated in the sunlit hemisphere, as were low frequency transmissions over various path lengths as reported by Belrose et al. (1956) in southern England and Ramanathan et al. (1956) in India. Long waves at LF and VLF showed a characteristic phase change (‘sudden phase anomaly’) caused by the lowering by about 8 km of their reflection heights in the D region. For example, Pierce (1956) in eastern USA observed a phase advance of the 16 kHz signal from Rugby UK, corresponding to a change of about 15 km in the transatlantic path length. Another consequence was the attenuation of low frequencies, while Ellison and Reid (1956) reported a decrease in 24 kHz field strength when the solar cosmic ray particles arrived in Scotland in the dark hemisphere.

Bailey (1959) describes the ‘early effects’ that started minutes after the flare on both the day side and, delayed by a few more minutes, on the night side. These were perhaps the first observation of night side flare effects in the

ionosphere. The most striking feature of the early effects was the great increase of D region electron density on the night side, virtually to daytime levels at some places, which began around 10 min after the flare and extended down to geomagnetic latitudes of 50–60° in the North American and European sectors. The increased ionization resulted in decreases in field strength of distant radio transmissions, atmospherics, and cosmic radio noise, which persisted for about three hours and merged into the ‘late effects’. At geomagnetic latitudes above 60°, the early effects included the enhancement of VHF forward-scatter signals on paths of around 1000 km.

At the time, the only ways of detecting any flare effects in the F2 layer came from long-path HF/VHF radio links and from ionosondes. Recording short-lived flare effects with ionosondes is chancy because normally only hourly soundings are made, and so the timing of the flare midway between hours was unhelpful. Despite these limitations, increases after flares of the critical frequency foF2 (which corresponds to the peak F2 layer electron density) are sometimes reported. Observations on 23 February 1956 include an increase of foF2 at Singapore (Minnis and Bazzard, 1958), and increases in E and F2 layer electron density in Russia (Eryushchev, 1958).

Little information from elsewhere has been preserved because, according to the database of the World Data Centre C1 at Chilton, UK, only a few ionospheric stations contributed hourly foF2 data for the period 0300 to 0500 UT on 23 February, namely Ottawa, Slough, Freiburg, Canberra, Brisbane and Townsville, and these sparse values mostly carry qualifications specified by the standard URSI conventions for ionograms. There were slight drops in foF2 at Slough, Freiburg, Brisbane and Ottawa between 0300 and 0400 UT, but whether they can be attributed to the flare is doubtful. If there were any increases of foF2 during the flare, they had disappeared by 0400 UT.

#### 5. Late effects in the ionosphere

The ‘late effects’ began around 0530 UT, and were described for example by Lied (1957) and Little and Leinbach (1958). They included strong absorption of cosmic radio noise and of ionospherically scattered radio transmissions at frequencies around 30 MHz. The new finding was that the abnormal absorption occurred for two or three days, but only in daylight, and was widely distributed in latitude and longitude at geomagnetic latitudes above about 60° but not seen below 50°. As reported by Bailey (1959), this newly discovered phenomenon, later called ‘polar cap absorption’ (PCA), is attributed to photodetachment by sunlight of electrons from negative ions, such as O<sub>2</sub><sup>-</sup>, at heights below 90 km, after the initial arrival of solar cosmic rays, as originally suggested for example by Ehmert and Revellio (1957). Further south, at Jodrell Bank in Northern England, Dagg et al. (1956) observed radio-star scintillation, auroral radio echoes and geomagnetic field variations, much the same as for auroral conditions,

but with no change of cosmic radio noise at 79 or 90 MHz. At Cambridge, UK, sunrise effects in the D region started earlier than usual, at about an hour before ground sunrise at 0800 local time. This was tentatively attributed to photo-detachment from negative ions produced some hours earlier by the flare, as with the abnormal polar cap absorption mentioned above. The inherent variability of the F2 layer makes it extremely difficult to detect any long-lived effect of a flare.

## 6. Geomagnetic effects, 25 February 1956

A major geomagnetic storm occurred on 25 February during which the  $A_p$  index reached 236 corresponding to  $K_p$  8 (Table 1). The flare of 23 February 1956 located near  $80^\circ\text{W}$  on the solar disk was considered at that time an unfavourable location for producing geophysical effects. Even as late as 1973 when the Catalog of Solar Particle Events, 1955–1969 (Švestka and Simon, 1975) was prepared, the compilers did not include the geomagnetic storm sudden commencement (SSC) at  $\sim 0306$  UT on 25 February as associated with the solar activity on 23 February.<sup>3</sup> The argument at that time was that solar activity so far to the west limb of the sun would not be associated with such a major geomagnetic storm. (It should be remembered that coronal mass ejections and their expansion into the interplanetary medium had not been identified in 1956.)

Examination of the optical flares listed in the *Quarterly Bulletin on Solar Activity* (1956) does not indicate any significant solar activity near the solar central meridian during the period 21–24 February. This is also consistent with the location of solar active regions shown in the Fraunhofer map for 23 February (Fig. 2). With our present knowledge of solar activity and coronal mass ejections, the association of the geomagnetic disturbance on 25 February with the solar activity from McMath Region 3400 on 23 February appears highly plausible.

## 7. Conclusion: what was learned from the event of 23 February 1956

Half-a-century later, the 1956 event is seen as one of the greatest solar-terrestrial happenings of the twentieth century. Since then there have been other significant solar-terrestrial events such as those in August 1972, March 1989, October 1989, October–November 2003 and January 2005. Ground-level solar cosmic ray enhancements occurred during each of those sequences of solar proton events and subsequent geomagnetic disturbances with the exception of the March 1989 events. It is difficult to decide on ‘the greatest’ because there are many criteria that could be used.

<sup>3</sup> As two of the compilers for the Catalog of Solar Particle Events, Shea and Smart recall many discussions among the participants of this project as to whether or not the geomagnetic disturbance on 25 February was associated with the 23 February solar activity.

The massive solar proton event – as it would now be termed – emitted copious fluxes of protons, heavier ions and relativistic electrons which produced geophysical effects on both day and night sides of the earth. The detection of relativistic electrons arriving minutes after a flare was a ‘first’ for this event, and eventually gave rise to the idea of ‘relativistic electron precipitation’ events (REP) described by Bailey and Pomerantz (1965). The ‘late effects’ of the flare suggested that energetic particles can be ‘stored’ close to the earth. Recently McCracken et al. (2008) have pointed out the necessity of small-time interval data to study the extreme anisotropies.

In the fifties there was great interest in phenomena in the earth’s magnetic envelope, and the concept of the ‘magnetosphere’ gradually took shape, though that name was not suggested until later (Gold, 1959). The aurora had been scientifically studied for about a century, and the idea of particle streams affecting the outer geomagnetic field had been thrashed out by 1900, largely by Fitzgerald and Lodge (Rishbeth, 2001).

From the ionospheric point of view, the most novel discoveries from the February 1956 event were polar cap absorption (PCA) and the night-time particle events that formed part of the ‘early effects’. The lack of any major response in the F2 layer would come as no surprise today. The ensuing magnetic storm two days later certainly did affect the F2 layer, but that is quite another matter. Big flares emit strong X-rays which drastically affect the D and E layers, but there is little enhancement of the EUV wavelengths that ionize the F layers. Knecht and Davies (1961a) give reasons why not every ionospheric station in the sunlit hemisphere may record any clear F layer effect of a flare.

Years later, satellite measurements made it possible to record flare effects in the whole F2 layer, not just below the F2 peak as before. Increases have been recorded in total (height-integrated) electron content, of which the F2 layer contributes by far the greatest part; Garriott et al. (1967) described a good example that occurred on 21 May 1967. An increase of ionospheric total electron column content (usually called ‘TEC’) began at flare onset, was fastest at the peak of optical  $H\alpha$  emission, and continued for several minutes throughout the duration of the flare. Nowadays, continuous TEC monitoring by GPS satellites can provide extensive information of flare effects, though the total content data do not give information on the height in the ionosphere at which the effects occur.

A note of caution is needed. Not everything observed on 23 February 1956 was necessarily due to the flare. In particular, the F2 layer is easily perturbed by a variety of causes which can disguise any effect of a solar flare, a point argued some years later by Munro (1961) and Knecht and Davies (1961b). Munro cautioned against interpreting ‘travelling ionospheric disturbances’ (TID) as consequences of a solar flare, his point being that TID are so common that they often coincide with unrelated events. Similar reservations apply to other F layer phenomena,

such as TID and other disturbances reported around the time of a solar eclipse and before earthquakes. Munro pointed out that the effects of solar flare emissions are widely felt over the dayside hemisphere, so are nothing like the localized source needed to launch a TID.

The events of 23 February 1956 still attract interest. Recent studies by Vashenyuk et al. (2008) better characterize the high energy particle spectrum and anisotropy components though their interpretation of this event may not be universally accepted: see, for example, McCracken et al. (2008), who offer a more complete interpretation of the *high energy solar* cosmic ray phenomena.

So the story of the event may not yet be complete. The last word goes to John Donne (1572–1631): “Busy old fool, unruly Sun! Why dost thou thus?”

### Acknowledgements

We thank J.H. Allen for providing details of major storms in 1956 and the NOAA National Geophysical Data Centre for providing the Fraunhofer maps. We gratefully acknowledge the individual recollections given in the Appendix, and messages received from G.M. Brown, J.W. Meriwether, M.H. Rees, and K.V. Sheridan. We thank M.A. Hapgood for his help in obtaining contemporary papers.

### Appendix A. Some individual recollections (abridged)

*Comments from J.H. Allen.* I went into my  $Ap^*$  indices list to check out the February 23, 1956, event and any related major magnetic storms. There was a sequence of large geomagnetic storms, spaced out across several weeks, but none so large as the September 1942 or March 1989 events. The Sun must have been in a very busy mode.

*Comments from H. Ahluwalia.* I joined the Physical Research Laboratory at Ahmedabad in the fall of 1954; it is affiliated with the Gujarat University in India. My advisor was Dr. Vikram Sarabhai, a doyen of Indian Space Research efforts, who later succeeded Dr. Homi Bhabha as the Director of the Department of Atomic Energy (DAE), Government of India. Vikram obtained a DAE grant to set up a network of field stations at different latitudes in India, ranging from equator in the south at Trivandrum in Kerala to the Himalayas in the north, to study time variations of galactic cosmic rays (GCRs).

I was chosen to establish the field station at Gulmarg in Kashmir (alt 9600 ft). This huge undertaking was a part of India's contribution to the International Geophysical Year (IGY) 1957–1958. Our group participated in the global effort to establish the characteristics of solar modulations of GCRs. For my part, I designed and operated a number of triple coincidence GM counter telescopes at Gulmarg for 1955–1958, beginning in the fall of 1955. Each counter was 2 feet long with a diameter of 1.5 inches. The separation between the counters and their orientation was such that each telescope in the east–west and north–south planes

were  $5^\circ$  and  $56^\circ$ , respectively, with 8 cm lead interposed between counter trays.

At the time of the solar flare on 23 February 1956, three telescopes were in operation at Gulmarg. The rate of each telescope was 700 counts per hour, standard deviation being rather large (about 4%). I was at the lab when the counting rate went wild! I thought that the counters were all in a discharge mode which I thought was rather odd since it had never happened before! I thought that I should see the pulses on an oscilloscope. It took me some time to find one. My instinct led me to switch off the common high tension power source to the telescopes and then switch it back on, one telescope at a time. The clicking of the mechanical counters slowed some but the rate was still quite high. I began checking the plateau of the counters to ascertain that the operating point was at the right place, but in the process valuable data were lost. At that time I had never heard of the phenomena of GLEs (Ground-Level Events). By afternoon the situation stabilized inexplicably.

It is interesting to note that in winters Gulmarg is completely isolated from the rest of the valley with feet of snow on ground. It is then used as a winter warfare training site by the Indian army. It was several months later that I learned that similar increases were observed at Trivandrum (5.7%), as well as at Huancayo (18%) and Godhavn (50%) with ion chambers of the Forbush global network. In the summer of 1956 a senior colleague (R.P. Kane) of mine came to visit me at Gulmarg. We went over the sketchy data of 23 February 1956. To reduce the statistical noise, the hourly data from three telescopes were combined for the period 21–25 February. We found an increase of about 102% in the uncorrected muon data during the time interval 8 a.m to 12 noon (LT) on 23 February.

That was my introduction to cosmic ray research! Life has not been quite the same since then.

*Comments from J.S. Belrose.* On 23 February 1956, the first ever observed solar proton event occurred. Solar protons were detected at ground level. The effects were marked on the VLF/LF propagation links I was monitoring. My paper with Kenneth Weekes was perhaps a first. Solar proton events were studied for more than two solar cycles (22-years) following, by Doris Jelly, Ted Hartz, George Reid, myself and others at DRTE, and by radio scientists all over the world. Solar minimum occurred in the summer of 1954. And fortuitously the change from minimum solar activity to maximum activity occurred abruptly within the one year 1956/1957. All this provided very interesting observational data for my thesis, the title of which is “Some Investigations of the Propagation of Long and Very Long Radio Waves”.

*Comments from J.K. Hargreaves.* I was in the army at Catterick in February 1956, and knew nothing about the event at the time. In my mind that event is associated with the discovery of the proton event (or PCA) by Dana Bailey, through his analysis of the effects on VHF forward-scatter circuits. It was also a ground-level event (GLE), affecting cosmic ray monitors.

In his paper of 1957, D.K. Bailey attributed the ionospheric effect to “moderately heavy solar atomic ions, such as calcium”. By the time of his 1959 paper, he was discussing the observations in terms of solar cosmic rays and had homed in on protons. That paper also quotes an example of the cosmic noise absorption during the event (Little and Leinbach, 1958); it is interesting that they quote this event as an example of the effect of daylight on absorption and do not (as far as I can see) mention protons!

*Comments from K.G. McCracken.* At the time I was a Ph.D. student at the University of Tasmania. I was operating a very cantankerous ionization chamber, an Australian version of the Carnegie chambers used by Scott Forbush. On the day in question I went over to check the chamber after lunch. On entering the hut I heard the servo motor wailing like a very upset banshee, hard against its stop. I immediately suspected an open circuit in one of the high impedance input plugs. So following a time honoured worldwide custom in the cosmic ray field when ground-level events occur, I turned it off and started to trouble-shoot.

Luckily my supervisor, Geoff Fenton, came in to check the other instruments in the lab. He said: “Ken, the counting rates are very high – have you been using an electric drill?” I said a rude word, stood up quickly, hit my head on the top of the electronics cabinet, and said “It’s a \*\*\*\*\* solar flare”. So from then on we made manual readings to get a high resolution record. By repeatedly shorting the ionization chamber centre electrode to earth, I was able to get the time profile with some accuracy (Fenton et al., 1956).

That event had long term consequences for me and my career. Examining the onset times of the GLE, it was clear that there was something queer going on. John Simpson’s group had recently shown that the cosmic ray equator was strongly influenced by the higher order terms of the geomagnetic field. I pondered: Could the higher order terms explain the strange onset times? Could I compute the “asymptotic directions” of cosmic rays for the 6th order Finch and Leaton expansion of the field? In 1956 we did not have an electronic computer, and when I estimated that each cosmic ray orbit would take 6 months to compute with the fastest hand computing machine available, 8 h per day, I gave up that idea.

Arriving at MIT in 1959, I found that there was an IBM704 in the basement. I re-scoped the calculation, and found each orbit would take 20 min. However, the handbook conveyed the cheerful information that the mean time between failures was 10 min. Not being risk adverse, I started to program the calculation. Six months later it was working, and checked out as best as was possible, without any other results to check it against.

And then the Sun lived up to its weighty obligations. It produced four marvellously interesting ground-level events (GLE) in 1960, and then more or less stopped that game for a long time. I swung into action with my orbit-tracing program.

Comparing the worldwide results with the predictions of the “cosmic ray cut-off rigidity” of the time, the results from sub-Antarctic Kerguelen Island stuck out as an enormous anomaly. Here was a worthy test of my program. About 30 orbit calculations later I found that my computed geomagnetic cut-off for Kerguelen explained the GLE results extremely well. Conclusion 1: the 6th order field described the cosmic ray effects very well; conclusion 2: My program was working OK.

Looking then at where the cosmic rays had come from in space, and the onset times that had gained my interest for 23 February 1956, I found that the solar cosmic rays had come from 60° west of the earth–sun line. Since I had used the 6th order field expansion, there were none of the uncertainties that arose when interpreting the results with a dipole field. The 60° offset was exactly that predicted by Gene Parker’s solar wind theory (then hotly debated), and seriously at variance to the other models of the time – the “solar breeze” and “very low interplanetary magnetic fields”. Each of the 1960 GLE were very well explained by the combination of Gene Parker’s model and my asymptotic direction calculations. This confirmed the correctness of the “garden-hose” IMF, years before the first accurate measurements in space. So four years after 23 February 1956, the questions it had posed led to a good understanding of the GLE of 1960 and validation of Parker’s solar wind hypothesis.

And the event of 23 February had another absolutely magnificent outcome. Peggy Shea had started to use my computing program at MIT in early 1961, and knowing that I was about to get interested in other things, she asked if she could take it over for geomagnetic cut-off and asymptotic direction calculations. This she did, and together with Don Smart totally dominated those subjects ever since. So the great body of work they have contributed, with many enhancements, owes its genesis to that big flare effect on 23 February 1956 and the anomalous nature of the worldwide onset times.

Re the contribution of the event to ionospheric physics folklore: the 1956 event had substantial cosmic ray outcomes. The Sun well and truly got our attention with that one, and stimulated a great deal of subsequent understanding.

*Comments from H. Rishbeth.* I was attached to the CSIRO Radiophysics Laboratory, Sydney, and spent many days and night at Fleurs, with the group which built and ran the Mills Cross radio telescope and later Shain Cross. Fleurs is situated about 40 km WSW of central Sydney and was home to three innovative cross-type radio telescopes, the 85.5 MHz Mills Cross, the 19.7 MHz Shain Cross and the 1426 MHz Chris-Cross, all of which played important roles in galactic or solar radio astronomy. On 23 February 1956, when we started work after lunch and the Mills Cross had just started its routine daily run, the receiver suddenly jumped off scale with a bang. This was presumed to be an equipment malfunction, so the record was torn off and dumped in the bin.

There was a phone call. Had we recorded the big solar event? Hastily the record was retrieved (it showed nothing useful). Apparently the “solar flare of the century” had happened at 0331 UT (1331 local time at Sydney).

The Chris-Cross 1426 MHz solar interferometer had not been fully commissioned. All the solar radio telescopes at the Radiophysics Laboratory’s solar site at Dapto, about 100 km to the south, were off the air and the site was virtually flooded. Because of the bad weather, the Sun had hardly been seen visually for many days. The only Radiophysics Laboratory observations of the whole event were made by the 19.6 MHz interferometer at Fleurs, recently installed to monitor the lately discovered bursts from Jupiter. Its record showed the radio bursts, but not much was learned about them. So the leading radio astronomy laboratory in the Southern Hemisphere had little to report.

*Comments from M.A. Shea.* In March 1956 I started working on the cosmic ray project at University of New Hampshire. On the night of 22 February the weather observers at the Mount Washington, NH observatory had just completed their evening weather observations. Their next job was to check the UNH cosmic ray neutron monitor located downstairs in an attached wing of the building. The process was to record the counting rate meters of the monitor, twice a day, and radio the results back to UNH the following day. Checks were roughly 12 h apart, usually around 1100 and 2300 local time. Around 2255 LT (0355 UT) the weather observers went down to the monitor, found the “clicks” on the digital count rate meter were going full steam and immediately shut everything off to protect the monitor. The next day, via radio, they proudly reported that something went wrong with the monitor the night before, but they were able to shut it down before any real damage was done. I understand that a similar occurrence happened at the University of New Mexico where a neutron monitor was being tested. A bunch of graduate students noted around 2100 LT that the monitor was “acting strangely” and immediately shut it off.

*Comments from J.W. Wright.* Bob Knecht, Ken Davies and Virginia Lincoln were tremendously excited, and especially so after ionograms trickled in. **A world-record foF2 of about 28 MHz was reported along with other then-novel F region effects.**

## References

- Adams, N. A temporary increase in the neutron component of cosmic rays. *Phil. Mag.* 41, 503–505, 1950.
- Bailey, D.K. Disturbances in the lower ionosphere observed at VHF following the solar flare of 23 February 1956 with particular reference to auroral-zone absorption. *J. Geophys. Res.* 62, 431–463, 1957.
- Bailey, D.K. Abnormal ionization in the lower ionosphere associated with cosmic-ray flux enhancements. *Proc. IRE* 47, 255–266, 1959.
- Bailey, D.K., Pomerantz, M.A. Relativistic electron precipitation into the mesosphere at subauroral latitudes. *J. Geophys. Res.* 70, 5823–5830, 1965.
- Belrose, J.S., Devenport, M.H., Weekes, K. Some unusual radio observations made on 23 February 1956. *J. Atmos. Terr. Phys.* 8, 281–286, 1956.
- Belov, A., Eroshenko, E., Mavromichalaki, H., Plainaki, C., Yanke, V. A study of the ground level enhancement of 23 February 1956. *Adv. Space Res.* 35, 697–701, 2005.
- Dagg, M., Vice, R.W., Watkins, C.D. Jodrell Bank observations of the geophysical phenomena following the solar flare of 1956 February 23. *Jodrell Bank Annals* 1, 104–115, 1956.
- Dellinger, J.H. Sudden ionospheric disturbances. *Terr. Magn. Atmos. Elect.* 42, 49–53, 1937.
- Dorman, L.I. Cosmic Ray Variations, State Publishing House for Technical and Theoretical Literature, Moscow (Translated by Technical Documents Liaison Office, Wright-Patterson Air Force Base, Ohio, USA), 1957.**
- Ehmert, A., Revellio, K. Solare ultrastrahlung und ionosphärische D schicht am 23 Februar 1956 (On solar cosmic rays and the ionospheric D layer on 23 February 1956). *Z. Geophys.* 23, 113–134, 1957.
- Ellison, M.A., Elliot, H., Watkins, C.D., Minnis, C.M., Weekes, K. Relations between the sun and the ionosphere. *Nature* 179, 804–806, 1957.
- Ellison, M.A., Reid, J.H. A long wave anomaly associated with the arrival of cosmic ray particles of solar origin on 23 February 1956. Decrease in 24 kHz field strength when SCR particles arrived in dark hemisphere. *J. Atmos. Terr. Phys.* 8, 291–293, 1956.
- Eryushchev, N.N. On ionospheric effects of the large solar flare of 23 February 1956. *Izvest. Krym. Astrofiz. Obs.* 20, 3–11, 1958.
- Fenton, A.G., McCracken, K.G., Parsons, N.R., Trost, P.A. Cosmic-ray increase observed at high southern latitudes on February 23, 1956. *Nature* 177, 1173–1174, 1956.**
- Forbush, S.E. Three unusual cosmic-ray increases possibly due to charged particles from the Sun. *Phys. Rev.* 70, 771–772, 1946.
- Forbush, S.E., Stinchcomb, T.B., Schein, M. The extraordinary increase of cosmic-ray intensity on November 19, 1949. *Phys. Rev.* 79, 501–504, 1950.
- Garriott, O.K., da Rosa, A.V., Davis, M.J., Villard Jr., O.G. Solar flare effects in the ionosphere. *J. Geophys. Res.* 72, 6099–6103, 1967.
- Gold, T. Motions in the magnetosphere of the earth. *J. Geophys. Res.* 64, 1219–1224, 1959.
- Knecht, R.W., Davies, K. Solar flare effects in the F region of the ionosphere. *Nature* 190, 797–798, 1961a.
- Knecht, R.W., Davies, K. Possible solar flare effects in the F region of the ionosphere. *Nature* 192, 348, 1961b.
- Lied, F. Ionospheric absorption observed on the 23rd February 1956 at Kjeller and Tromsø. *J. Atmos. Terr. Phys.* 10, 48, 1957.
- Little, C.G., Leinbach, H. Some measurements of high-latitude ionospheric absorption using extraterrestrial radio waves. *Proc. IRE* 46, 334–349, 1958.
- Lockwood, J.A., Yngst, H.E., Calawa, A.R., Sarmanote, G. Cosmic-Ray neutron intensity increase associated with solar flare of February 23, 1956. *Phys. Rev.* 103, 247–248, 1956.
- Lovell, J.L., Duldig, M.L., Humble, J.E. An extended analysis of the September 1989 cosmic ray ground level enhancement. *J. Geophys. Res.* 103, 23733–23742, 1998.
- Manning, L.A. Bibliography of the ionosphere, 1925–1960. Stanford Electronics Laboratory, Stanford University, California, 1960.
- Mayaud, P.N. A Hundred Year Series of Geomagnetic Data 1868–1967, IAGA Bulletin No. 33, IUGG Publications Office, Paris, 1973.
- Meyer, P., Parker, E.N., Simpson, J.A. Solar cosmic rays of February, 1956 and their propagation through interplanetary space. *Phys. Rev.* 104 (1), 768–783, 1956.
- Minnis, C.M., Bazzard, G.H. Solar effects in the F2 layer of the ionosphere. *Nature* 181, 690–691, 1958.
- McCracken, K.G. The cosmic-ray flare effect. 1. Some new methods of analysis. *J. Geophys. Res.* 67, 423–434, 1962a.
- McCracken, K.G. The cosmic-ray flare effect. 2. The flare effects of May 4, November 12, and November 15, 1960. *J. Geophys. Res.* 67, 435–446, 1962b.

- McCracken, K.G., Rao, U.R., Fowler, B.C., Shea, M.A., Smart, D.F. Cosmic Ray Tables (Asymptotic Directions, Variational Coefficients and Cut-off Rigidities), IQSY Instruction Manual No. 10, May 1965.
- McCracken, K.G., Moraal, H., Stoker, P.H. Investigation of the multiple-component structure of the 20 January 2005 cosmic-ray ground level enhancement. *J. Geophys. Res.*, 113, 2008.
- Munro, G.H. Possible solar flare effects in the F region of the ionosphere. *Nature* 192, 347, 1961.
- Neidig, Donald.F., Cliver, Edward.W. A catalog of solar white-light flares (1859–1982), including their statistical properties and associated emissions, AFGL-TR-83-0257. Air Force Geophysics Laboratory, Bedford, MA, 1983.
- Notuki, M., Hatanaka, T., Unno, W. A very unusual flare on February 23, 1956. *Publ. Astron. Soc. Jpn.* 8, 52, 1956.
- Pfotzer, G. On the separation of direct and indirect fractions of solar cosmic radiation on February 23, 1956 and on the difference in steepness of momentum spectrum of these two components. *Nuovo Cimento* 8 (Suppl.), 180–187, 1958.
- Pierce, J.A. VLF phase shifts associated with the disturbance of February 23, 1956. *J. Geophys. Res.* 61, 475–483, 1956.
- Waldmeier, M. (Ed.). *Quarterly Bulletin on Solar Activity*. Eidgenössische Sternwarte, Zürich, November 1956.
- Ramanathan, K.R., Bhonsle, R.V., Kotadia, K.M., Rastogi, R.G. The great solar flare of Feb. 23, 1956 and associated ionospheric effects at Ahmedabad. *Proc. Indian Acad. Sci.* 43, 306–308, 1956.
- Rishbeth, H. The centenary of solar-terrestrial physics. *J. Atmos. Solar-Terr. Phys.* 63, 1883–1890, 2001.
- Shea, M.A., Smart, D.F. Fifty years of cosmic radiation data. *Space Sci. Rev.* 93, 229–262, 2000.
- Shea, M.A., Smart, D.F. Vertical cutoff rigidities for cosmic ray stations since 1955. In: 27th International Cosmic Ray Conference, Contributed Papers, vol. 10, pp. 4063–4066, 2001.
- Shea, M.A., Smart, D.F., Wada, M., Inoue, A. A suggested standardized format for cosmic ray ground-level event data. In: 19th International Cosmic Ray Conference, Conference Papers, vol. 5, pp. 510–513, 1985.
- Shea, M.A., Smart, D.F., Humble, J.E., Flückiger, E.O., Gentile, L.C., Nichol, M.R. A Revised Standard Format for cosmic ray ground-level event data. In: 20th International Cosmic Ray Conference, Conference Papers, vol. 3, pp. 171–174, 1987.
- Simpson, J.A. (Ed.). *Cosmic-Radiation Neutron Intensity Monitor*, Annals IGY, IV. Pergamon Press, London, 351, 1957.
- Smart, D.F., Shea, M.A. Probable pitch angle distribution and spectra of the 23 February 1956 solar cosmic ray event. In: 21st International Cosmic Ray Conference, Conference Papers, vol. 5, pp. 257–260, 1990.
- Storini, M., Giangrave, S., Diego, P., Laurenza, M., More on the Gnevyshev Gap during the 11-year solar activity cycle. In: Caballero, R., D’Olivo, J.C., Medina-Tanco, G., et al. (Eds.), Proceedings of the 30th International Cosmic Ray Conference, Universidad Nacional Autónoma de México, Mexico City, pp. 533–536, 2008.
- Švestka, Z., Simon, P. *Catalog of solar particle events 1955–1969*. Astrophysics and Space Science Library, vol. 49. D. Reidel Publishing Company, Dordrecht, The Netherlands, 1975.
- Vashenyuk, E.V., Balabin, Yu.V., Miroshnichenko, L.I. Relativistic solar protons in the ground level event of 23 February 1956: new study. *Adv. Space Res.* 41, 926–935, 2008.