Manusript of the article: Gabriella Satori, Earle Williams, Colin Price, Robert Boldi, Alexander Koloskov, Yuri Yampolski, Anirban Guha, Veronika Barta, Effects of Energetic Solar Emissions on the Earth–Ionosphere Cavity of Schumann Resonances.

Appeared in: Surveys in Geophysics, July 2016, Volume 37, Issue 4, pp 757–789

DOI 10.1007/s10712-016-9369-z

Journal : Small 10712 | Dispatch : 5-3-2016 | Pages : 33
Article No. : 9369 | ☐ LE | ☐ TYPESET
MS Code : GEOP-D-15-00044 | ☑ CP | ☑ DISK

Surv Geophys
DOI 10.1007/s10712-016-9369-z

Effects of Energetic Solar Emissions on the Earth–Ionosphere Cavity of Schumann Resonances

Gabriella Sátori[1] · Earle Williams[2] · Colin Price[3] · Robert Boldi[4] · Alexander Koloskov[5] · Yuri Yampolski[5] · Anirban Guha[6] · Veronika Barta[1]

Received: 24 April 2015 / Accepted: 25 February 2016

AQ1 **Abstract** Schumann resonances (SR) are the electromagnetic oscillations of the spherical cavity bounded by the electrically conductive Earth and the conductive but dissipative lower ionosphere (Schumann in Z Naturforsch A 7:6627–6628, 1952). Energetic emissions from the Sun can exert a varied influence on the various parameters of the Earth's SR: modal frequencies, amplitudes and dissipation parameters. The SR response at multiple receiving stations is considered for two extraordinary solar events from Solar Cycle 23: the Bastille Day event (July 14, 2000) and the Halloween event (October/November 2003). Distinct differences are noted in the ionospheric depths of penetration for X-radiation and solar protons with correspondingly distinct signs of the frequency response. The preferential impact of the protons in the magnetically unshielded polar regions leads to a marked anisotropic frequency response in the two magnetic field components. The general immunity of SR amplitudes to these extreme external perturbations serves to remind that the amplitude parameter is largely controlled by lightning activity with the Earth–ionosphere cavity.

Keywords Schumann resonances · Solar X-ray · Solar proton · Earth–ionosphere cavity · Characteristic ionospheric heights

✉ Gabriella Sátori
gsatori@ggki.hu

[1] Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Geodetic and Geophysical Institute, Csatkai u. 6-8., Sopron, Hungary

[2] Parsons Laboratory, MIT, Cambridge, MA, USA

[3] Tel Aviv University, Tel Aviv, Israel

[4] Zayed University, Abu Dhabi, United Arab Emirates

[5] Institute of Radio Astronomy, National Academy of Sciences of Ukraine, 4 Chernovopraporna St., Kharkiv 61002, Ukraine

[6] Tripura University, Suryamaninagar, India

Journal : Small 10712 Dispatch : 5-3-2016 Pages : 33
Article No. : 9369 □ LE □ TYPESET
MS Code : GEOP-D-15-00044 ☑ CP ☑ DISK

1 Introduction

AQ2 The Earth's naturally occurring Schumann resonances (SR), maintained by global lightning and confined to the thin dielectric region of atmosphere between the conductive Earth and the ionosphere, are rich with information about the terrestrial and space environments. These continuously maintained global resonances are characterized by amplitudes (intensities), modal frequencies and dissipation parameters (Q factors and damping parameters), all of which respond in distinct ways to different kinds of forcing. This study is concerned with the impacts of exceptional solar activity on the parameters of the SR.

Two of the most exceptional solar storms on record that also serve to bracket the solar maximum of Solar Cycle 23 have been selected for detailed examination, the Bastille Day event of July 14, 2000 and the Halloween event of October/November, 2003. The Bastille Day event, an X-class (5) solar flare with a distinct separation of X-radiation and solar proton emissions, has already been identified as a choice target for both experimental ELF studies (Nickolaenko and Hayakawa 2002; Roldugin et al. 2004; De et al. 2010; Nickolaenko and Hayakawa 2014) and modeling work (Ondrášková et al. 2003; Ondrášková 2005). The Halloween event, a solar disturbance of exceptionally long duration in spanning a two-month period (Baker et al. 2004), saturated the hard X-ray detectors on the GOES satellite (Lopez et al. 2004). Subsequent analysis led to an upgrade in the X-class of the last flare of the sequence (November 4, 2003) to 45 (Thomson et al. 2004), making it the most energetic solar flare on record. The effects of the Halloween event have not been previously examined at ELF, though a comparison of the solar emissions in the record-breaking Bastille Day and Halloween events can be found in Le et al. (2007).

Key objectives in this investigation of SR response to these exceptional events have been the establishment of a systematic global response and an exploration of evidence for a timescale independence in the physical response, when the SR cavity is exposed to similar levels of ionizing radiation but on very different timescales. An important reference for the longer timescale is the response of SR to the 11-year solar cycle (Sátori et al. 2005). Also, in light of the long-standing interest in using multi-station measurements of SR intensity as a continuous monitor of global lightning activity (Williams and Mareev 2014), we have been interested in the degree of immunity in the SR intensity to extraterrestrial influences of the kind considered here.

The organization of this paper runs as follows. Section 2 is concerned with a description of the five ELF stations worldwide that have provided SR documentation on the two selected events. Section 3 reviews previous work on this subject, including the discussion of the ionization profiles for mono-energetic particles that are so useful in relationship with the 'electric' (h_e) and magnetic (h_m) ionospheric heights for SR. In Sect. 4, the results on measured SR response in frequency and intensity (field amplitude squared) are presented. The results are discussed in comparison with the theoretical predictions in Sect. 5, followed by the conclusions in the final Sect. 6.

2 Observational Assets

The interest in this study in establishing a global response to energetic particles and photons from the Sun during extraordinary events led to the examination of Schumann resonance observations at widely separated ELF receiving stations. Data from five separate observatories have been used, as summarized in Table 1. Four of these stations are

Table 1 Location and SR parameters of five separate SR stations

Location	Lat	Long	Field component	Mode number
Mitzpe Ramon, Israel	30.6 N	34.8 E	E_Z, H_{EW}, H_{NS}	1st, 2nd, 3rd
Nagycenk, Hungary	46.7 N	16.7 E	E_Z	1st, 2nd, 3rd
Parkfield, California, USA	35.9 N	120.4 W	H_{EW}, H_{NS}	1st
Vernadsky, Antarctica, Ukraine	65.3 S	64.2 W	H_{EW}, H_{NS}	1st, 2nd, 3rd
West Greenwich, Rhode Island, USA	41.6 N	71.7 W	E_Z, H_{EW}, H_{NS}	1st, 2nd, 3rd

operated continuously by co-authors of this paper and include Nagycenk Observatory in Hungary, Mitzpe Ramon Observatory in Israel, the MIT field station in West Greenwich, Rhode Island and the Vernadsky, Antarctica station operated by the Ukraine. Additional observations for Parkfield, California, established as part of an earlier earthquake monitoring effort there, were obtained from the Web site of the Berkeley Seismological Laboratory (http://www.quake.geo.berkeley.edu).

It is important to note that Schumann resonance modal frequencies were estimated with different methods in this study, with nearly as many variants as there are observatories involved. For the Nagycenk observations, the complex demodulation method (Sátori et al. 1996; Verő et al. 2000) was used. For Parkfield data, the Prony algorithm was used (Füllekrug 1994). For Mitzpe Ramon and Rhode Island, conventional three-parameter Lorentzian fits (Mushtak and Williams 2002; Sátori et al. 2009) were applied to extract frequencies. Finally, for Vernadsky data, yet a different method was used for modal frequency estimation, and in the absence of published documentation, that will be reviewed briefly here:

Power spectra S_{ew} and S_{ns} are computed for the east–west and north–south components of magnetic field, respectively, and are computed at 10-min intervals. The weighted mean modal frequency for the ith mode, fpi, of the respective magnetic field, is then computed as follows:

$$fpi_{\mathrm{ns,ew}} = \frac{\int_{fp0i-\Delta f}^{fp0i+\Delta f} \mathrm{d}f \cdot S_{\mathrm{ns,ew}}(f) \cdot f}{\int_{fp0i-\Delta f}^{fp0i+\Delta f} \mathrm{d}f \cdot S_{\mathrm{ns,ew}}(f)}$$

For first SR mode for example, values used for the integration limits are $fp01 = 8$ Hz and $\Delta f = 1.5$ Hz.

For later quantitative comparisons with theoretical predictions, use will be made of the SR modal frequencies from Rhode Island and Israel based on Lorentzian fits. All such fits are applied to computed power spectra and so the Lorentzian fits to those spectra represent intensity, not amplitude.

It is also important to note that the modal frequencies are not exactly equal to the eigenmodal frequencies. The latter quantities are invariants of the cavity and should be measured by every observer everywhere. The modal frequencies also depend on the source (S) to observer (O) distance in the lossy Earth–ionosphere cavity (Balser and Wagner 1962; Madden and Thompson 1965; Nickolaenko 1997; Nickolaenko and Hayakawa 2002). Kulak et al. (2006) developed a decomposition method to separate the eigenmodal frequency from the distance-dependent variations. This method was successfully applied for a sudden

Journal : Small 10712 Dispatch : 5-3-2016 Pages : 33
Article No. : 9369 LE TYPESET
MS Code : GEOP-D-15-00044 CP DISK

ionospheric disturbance at a single station by Dyrda et al. (2015), and more recently for two stations, one in Poland and the other in the USA (Kulak and Dyrda, personal communication 2016). The decomposition method claimed by Kulak et al. (2006) to separate the standing (resonant) and traveling wave components cannot be applied to the events studied here because the original time series data are not available for the five receiving stations involved.

3 Review of Previous Work

3.1 Impact of Energetic Particles on Upper and Lower D-Region Ionization

Energetic particles (electrons and protons primarily) and radiation (X-rays primarily), emanating from the Sun and from space and impinging on the Earth's atmosphere have characteristic depths of penetration as a function of energy. This aspect is particularly important for the problem at hand because well-defined ionospheric heights are deemed important for the behavior of SR (Madden and Thompson 1965; Greifinger and Greifinger 1978; Sentman 1990; Schlegel and Füllekrug 1999; Mushtak and Williams 2002; Greifinger et al. 2007). Two special heights were first identified in research on SR (Madden and Thompson 1965) when Maxwell's equations were applied to the Earth–ionosphere waveguide cavity. The role of these heights has become so important since that time that current models for the Schumann cavity are defined entirely with four complex heights, two for daytime and two for nighttime ionospheres (Greifinger et al. 2007; Kulak and Mlynarczyk 2013). The real part of the complex height is that physical height and the imaginary part represents the scale height of that feature, with the scale heights generally small in comparison with the physical heights. The effect of energetic particles on the entire cavity then reduces simply to how these complex heights are affected by the energetic particles (mainly photons, protons and electrons) and that is the main analysis approach in the present work. The energy dependence of penetration depth has been studied extensively for protons (Reid 1986), for electrons (Rees 1989) and for X-radiation (Richmond and Venkateswaran 1971; Rees 1989; Hargreaves 1992), but this large body of knowledge has not been strongly incorporated in previous studies of Schumann resonance response to these effects. The increasing ionization with depth due to increases in air density is accompanied by an attenuated flux with depth (dependent on the cross sections for ionization by air molecules at the energies of interest), leaving well-defined 'Chapman layers' of maximum ionization as a function of energy. The predictions for protons (Reid 1986) and electrons (Rees 1989) are reproduced in Fig. 1, with the assumption of no magnetic shielding. Since proton energies exceeding 100 MeV are known to occur in energetic solar events, penetration downward to $\sim$30 km altitude is possible (Ondráškova 2005) in the unshielded high-latitude regions, with attendant effects on the lower characteristic height of SR. It is important to note the additional evidence in Fig. 1 that when proton energies are sufficient (>100 MeV) for maximum effect at 30 km, the ionization impact in the upper characteristic layer is reduced by 2–3 orders of magnitude, and so is of relatively negligible importance, even though the same protons pass through the upper layer on their way down. On account of the substantially greater cross sections for air ionization by protons than electrons, proton energies needed to reach the 80–90 km altitude level (2–3 MeV) are substantially larger than for electrons ($\sim$50 keV). The X-radiation considered in this study (0.1–0.8 nm in wavelength or 1.5–12 keV in energy) has still smaller cross section for ionization and so still smaller photon energy is needed to attain the same altitude. X-ray ionization profiles are not shown, but suffice it to say that the

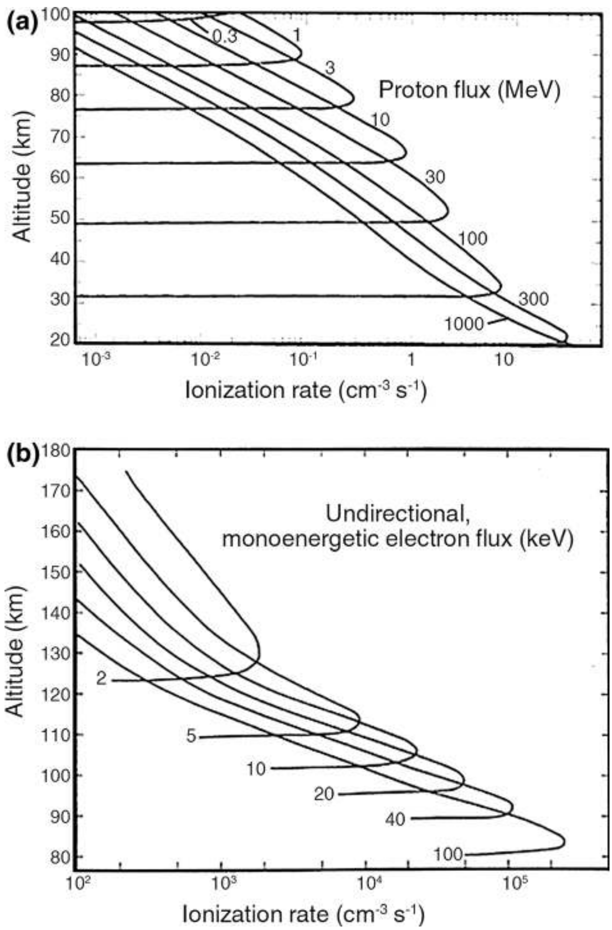

Fig. 1 Vertical profiles of ionization rate associated with the vertical entry of (**a**) mono-energetic protons adapted from Reid (1986) and (**b**) mono-energetic electrons adapted from Rees (1989) into the Earth's atmosphere. Magnetic shielding is assumed to be zero in both cases

ionization is maximum at 90 km altitude for X-rays in the wavelength range 0.2–1 nm (Whitten and Popoff 1971; Brasseur and Solomon 1986; Hargreaves 1999).

3.2 Modifications of Schumann Resonances by Energetic Solar Emission

Important early work on the problem of energetic particle modification of the Earth–ionosphere cavity has appeared, pertaining to both short-term (hours and days) and long-term variations (11-year solar cycle).

3.2.1 Short Timescale

The early modeling work of Madden and Thompson (1965) set the stage for understanding cavity response to ionizing radiation on short timescales by first identifying two key dissipation heights in the D-region. The pioneering work of Nelson (1967) in investigating SR parameter variations (modal frequency and Q factor) linked with polar cap absorption (PCA) events (involving solar protons) was built on Madden and Thompson (1965), but has not been cited frequently in the literature on this topic because this doctoral thesis was never published. Nelson (1967) investigated three PCA events and found consistent results in all cases: systematic decreases in SR frequency and Q factor for the fundamental 8 Hz mode. Nelson (1967) recognized on the basis of his modeling work that ionization increases in the lower characteristic height could account for the observed decreased quantities, but also that ionization increases in the upper characteristic layer (now recognized to be enacted by less deeply penetrating solar X-radiation) would lead to increases in frequency and Q factor. Sorting out the contributions of competing effects from energetic protons and photons (X-rays) has become an important goal in the present study.

Independently of Madden and Thompson (1965), and without awareness of the latter work, Greifinger and Greifinger (1978) developed analytic predictions for the two characteristic heights. [The analytical form of the lower height matched that of Madden and Thompson (1965)]. Due to the convenience of the analytical form, much of the subsequent work on mono-energetic particle modification of the Earth–ionosphere cavity (Schlegel and Füllekrug 1999; Sátori et al. 2005; Shvets et al. 2005) has relied on the Greifinger approach.

Roldugin et al. (1999) first identified the distinct contributions of energetic protons and X-radiation to Schumann resonance frequency perturbations in relativistic solar proton precipitation on November 6, 1997. Later, the same authors documented a similar sequence of X-rays followed by energetic protons in the extraordinary Bastille Day event of 2000, and again with distinct SR frequency variations made possible by the non-overlapping of these two fluxes in time during the event. The evidence for the different preferential ionization heights for protons (with energies in the 1–100 MeV range) and for solar X-radiation (with energies in the range of 10–30 keV) had been discussed qualitatively by Sentman (1990), but was specified more quantitatively in Reid (1986) for protons and by Richmond and Venkateswaran (1971), Rees (1989) and Hargreaves (1992) for the X-radiation as discussed above. Ondrášková's (2005) model calculations for the Bastille Day event provide important evidence that the solar protons can strongly influence the lower characteristic height of SR while exerting only minor influence on the upper height. Roldugin's documentation of systematic increases in SR frequency in response to X-ray events (including the analysis on the Bastille Day event), and the findings of a pronounced global response to X-rays on the solar cycle timescale (Sátori et al. 2005), both call into question claims that the effects of X-radiation on the Schumann cavity are negligible (Nickolaenko and Hayakawa 2002). Roldugin's pioneering work underlines the need for fine time resolution (10 min or better) in both the solar emissions and the global frequency variations.

On rare occasion, the Earth's atmosphere is subjected to photon bombardments from the cosmos with energies (tens of MeV, Palmer et al. 2005) one thousand times greater than that of solar X-radiation. One such gamma ray event on August 27, 1998, studied by Price and Mushtak (2001) showed "no noticeable changes in the ELF signals". This negative result may have explanation in the fact that the main ionization altitude from such energetic events does not coincide with either of two characteristic heights of the SR cavity (Greifinger et al. 2007). The gamma flare on December 27, 2004, studied later (Tanaka et al. 2011; Nickolaenko et al. 2012) also showed no discernible effect on SR propagation parameters, as in Price and Mushtak (2001), but it did produce a conspicuous ELF pulse.

Journal : Small 10712 Dispatch : 5-3-2016 Pages : 33
Article No. : 9369 LE TYPESET
MS Code : GEOP-D-15-00044 CP DISK

Chapman and Jones (1964), Schlegel and Füllekrug (1999) and Shvets et al. (2005) have all noted frequency increases associated with solar proton events. Madden and Thompson (1965) registered surprise with the finding of Chapman and Jones (1964) but at that time the documentation of accompanying X-radiation was rather incomplete. Shvets et al. (2005) dubbed these events "anti-PCA events". Their interpretation of these events involved a decrease of the upper characteristic height, but with no role for X-rays. The common presence of both proton and X-ray emission in solar flares is now well established. The SR frequency observations of Schlegel and Füllekrug (1999) were limited to daily resolution, and so the changes in frequency from the X-ray-dominant to the solar proton-dominant portion of events they studied [e.g., October 1989, shown in detail for both protons and X-rays in Belov et al. (2005)] could not be examined.

The polar non-uniformity of solar proton events in the Schumann resonance context has been appropriately emphasized by Rabinowicz et al. (2008). The key role of the Earth's dipolar magnetic field in guiding energetic protons and electrons into polar regions must be considered in interpreting results with a uniform model.

3.2.2 Long Timescale

The variation in D-region ionization by solar X-radiation and protons over the 11-year solar cycle has also been manifest in numerous observations of the SR (Sátori et al. 2000; Füllekrug et al. 2002; Kulak et al. 2003; Sátori et al. 2005; Ondrášková et al. 2011). Figure 16 serves as a reminder about the two-order-of-magnitude variation in X-ray flux from the Sun over the solar cycle. The strong spikes associated with individual X-ray events are superimposed on a continuously varying background level of X-radiation (Veronig et al. 2004). The 11-year variation of solar protons in the energy range >10 MeV consists of two-order-of-magnitude variations in average fluence from individual solar proton events (Feynman et al. 1990), but such high-energy events are sporadic in time and often disappear for months on end during solar minima (Getselev et al. 2006). The magnetic intensity variations at Vernadsky (Antarctica) suggest a substantial solar cycle variation (Williams et al. 2014). Based on discussions (D. Baker, B. Blake, H. Spence, personal communication December 2014), we now suspect that energetic electrons from the inner radiation belt are primarily responsible for the modification of the Schumann cavity on the solar cycle timescale at high latitudes.

4 Results on Two Extraordinary Solar Events

Two exceptional solar events have been selected for multiple-station Schumann resonance analysis in this study with two main goals in mind. The first is to establish the global representativeness of the Schumann signatures, and single-station analyses of the Bastille Day event (Nickolaenko and Hayakawa 2002; Roldugin et al. 2004; De et al. 2010) are available for comparison with the new observations reported here. The second goal is to document the Schumann resonance response to X-rays and protons on a distinctly different timescale than is typical for the Bastille Day kind of event on the short timescale, and for the 11-year solar cycle response on the long timescale.

Journal : Small 10712 Dispatch : 5-3-2016 Pages : 33
Article No. : 9369 □ LE □ TYPESET
MS Code : GEOP-D-15-00044 ☑ CP ☑ DISK

4.1 The Bastille Day Event

4.1.1 Frequency Variations

This giant solar proton event occurred on July 14, 2000. This event is known in the literature as the Bastille Day Event and the chronology of the solar emissions has been studied by Bieber et al. (2002). It was preceded by a short but intense X-ray burst in the X-class, the highest possible designation. (Of all solar events occurring since this time, only the soon-to-be discussed Halloween Event exceeded this level in the X-radiation.) Figure 2 shows the SR frequency variations for three resonant modes and for three field components at West Greenwich, Rhode Island. Remarkably similar to the records for the same event shown in single-field components by Roldugin et al. (2004) in Kamchatka, and by De et al. (2010) in India, with the signs of the frequency changes well-timed and with well-separated arrivals for X-rays and protons at the Earth's ionosphere in all cases. (This separation in time ($\sim$90 min) greatly simplifies the interpretation of the observations for the Bastille Day event in comparison with the situation for the Halloween event to be

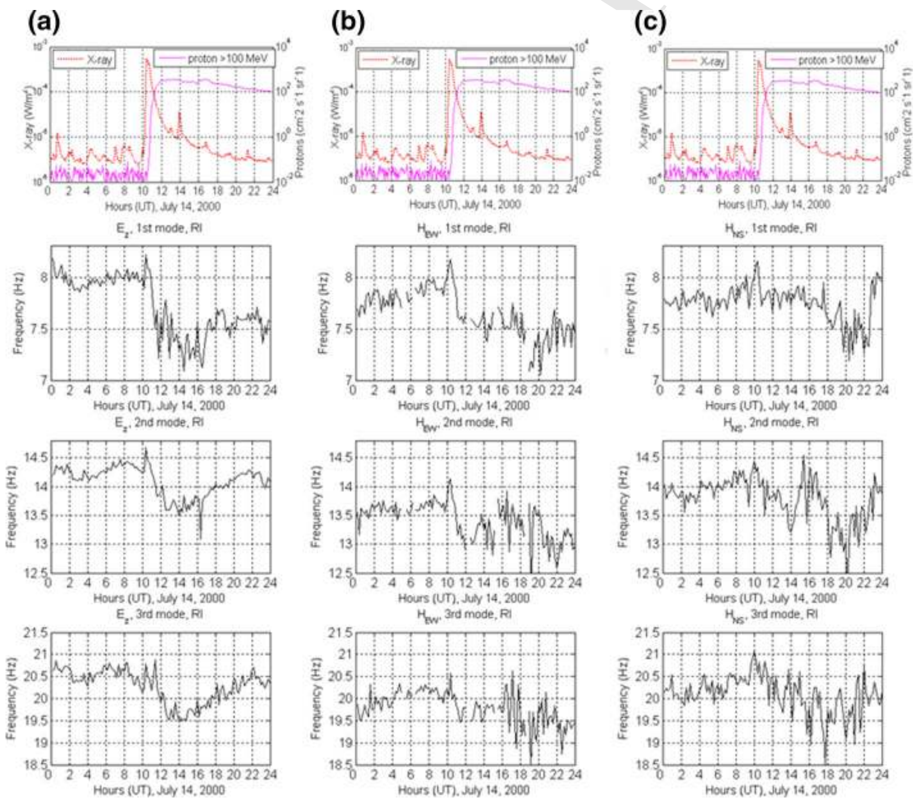

Fig. 2 Simultaneous records of the Schumann resonance frequency variations in West Greenwich, Rhode Island (in Hertz) during the Bastille Day Event (July 14, 2000) for (**a**) the vertical component of the electric field, for three resonance modes (*left* hand column), for (**b**) the Hew component of the magnetic field, for three resonance modes (*middle* column) and for (**c**) the H_{NS} component of the magnetic field, for three resonance modes. The repeated records at the *top* of each column show the simultaneous history of the X-rays (first arrival) followed by the solar protons

Journal : Small 10712 Dispatch : 5-3-2016 Pages : 33
Article No. : 9369 LE TYPESET
MS Code : GEOP-D-15-00044 CP DISK

discussed.) All modal frequencies increased during the short duration X-ray burst (at 10:24 UT) and then decreased markedly for several hours (11–16 UT) in all components of electric and magnetic field components in Rhode Island (see Fig. 2). The frequency increases evident in Fig. 2 and quantified in Table 4 of the "Appendix" were determined between the time of the maximum X-ray flux and the 3-h mean frequency value preceding it. The huge frequency decreases were estimated between the time of the maximum flux of the X-ray burst (10:24 UT) and the mean frequency level measured during the 3 h of maximum flux of the solar proton event.

4.1.2 The Bastille Day Event Results on Intensity Variations

Given the expectation for the deformation of the Schumann resonance cavity by these exceptionally energetic extraterrestrial ionizing events, it is of interest to explore the possibility of variations in the intensity of the SR simultaneous with that deformation. Figure 3 shows the intensity variations for the first resonance mode in West Greenwich, Rhode Island, for 4 days surrounding the Bastille Day event, together with the record of the proton flux (E > 100 MeV). The proton flux increased by about four orders of magnitude between 10:00 UT and 10:30 UT on July 14, 2000 (http://spidr.ngdc.noaa.gov/

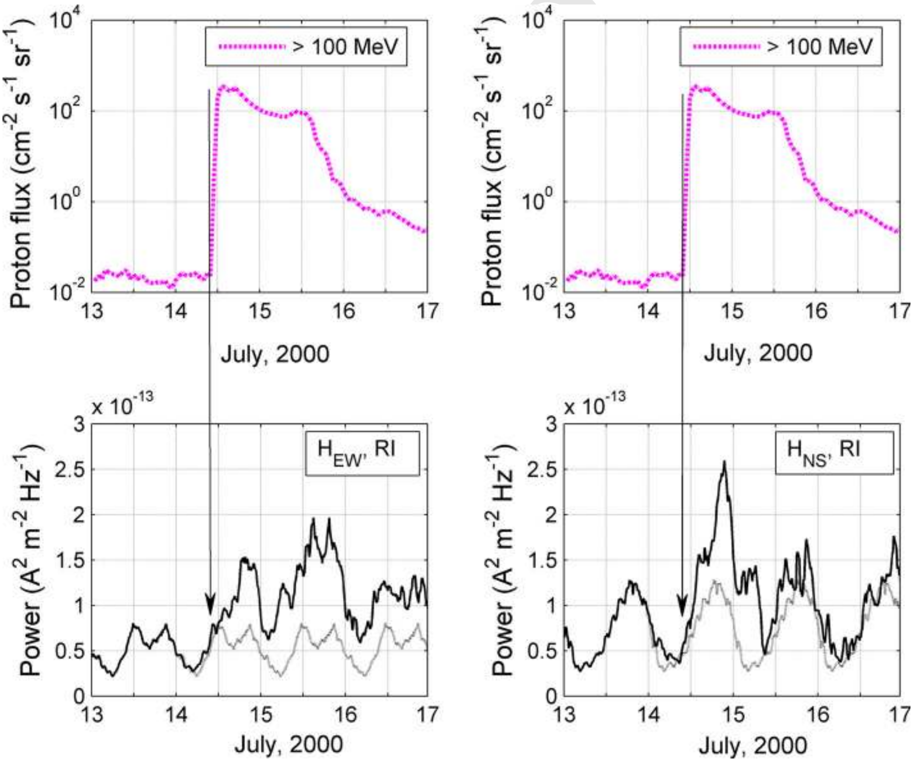

Fig. 3 Simultaneous records of the Schumann resonance intensity variations (in $A^2/m^2/Hz$) during 4 days surrounding the Bastille Day event (July 14, 2000) at West Greenwich, Rhode Island, with the H_{ew} field intensity variation on the *left* and the H_{NS} variation on the *right*. The intensity variation for July 13 is considered as a reference day and is repeated four times (*dashed curves*). The two (repeated) records at the *top* show the simultaneous history of energetic proton forcing

Journal : Small 10712 Dispatch : 5-3-2016 Pages : 33
Article No. : 9369 LE TYPESET
MS Code : GEOP-D-15-00044 CP DISK

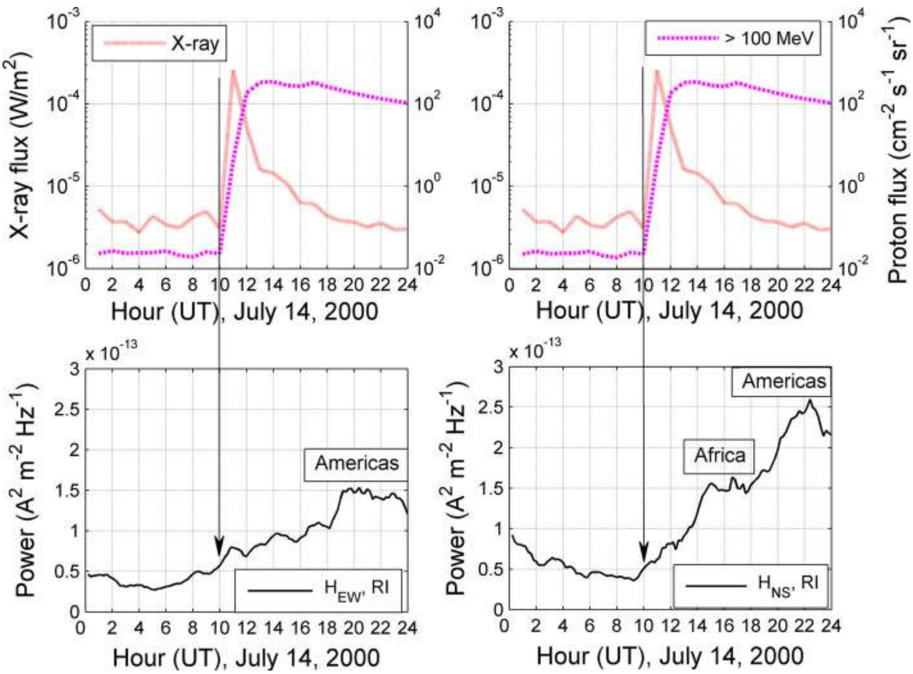

Fig. 4 Simultaneous records of the Schumann resonance intensity variations (in $A^2/m^2/Hz$) for the single day of the Bastille Day event (July 14, 2000) at West Greenwich, Rhode Island, for the Hew component (*middle*) and the H_{NS} component (*bottom*). The simultaneous history of forcing by X-radiation and protons is repeated at the *top*

spidr/). The arrows in Figs. 3 and 4 indicate the time point 10:00 UT. At first glance, the enhanced intensity (on the order of several tens of percent) noted on the day of the event and the day following are strongly suggestive of a positive influence, but on closer inspection at the time of the strong onset of the proton flux, no appreciable response in intensity is noted. Since the timing of both data sets is accurately known, and since one has every expectation that the effects of the ionizing radiation on the SR cavity are instantaneous, this latter observation casts some doubt on an appreciable effect of the protons on SR intensity. One can take this analysis one step further by examining only the single day of the event, in Fig. 4. For a summer day in Rhode Island, the diurnal records of H_{EW} and H_{NS} are unusually free of local meteorological contamination, and one can see the presence of the African and American sources in the two records. But the intensity response to the energetic proton event is not remarkable in either record of magnetic field.

4.2 The Halloween Event

4.2.1 Frequency Variations

Figure 5 documents a series of dramatic emissions from the Sun over a period of several weeks in October and November of 2003 (Baker et al. 2004) that has come to define the so-called Halloween Event. The hard solar X-ray flux (0.1–0.8 nm) increased by more than two orders of magnitude for a period longer than 2 weeks between October 18 and November 4. The X-radiation from this unusual event (Lopez et al. 2004; Thomson et al.

Journal : Small 10712 Dispatch : 5-3-2016 Pages : 33
Article No. : 9369 LE TYPESET
MS Code : GEOP-D-15-00044 CP DISK

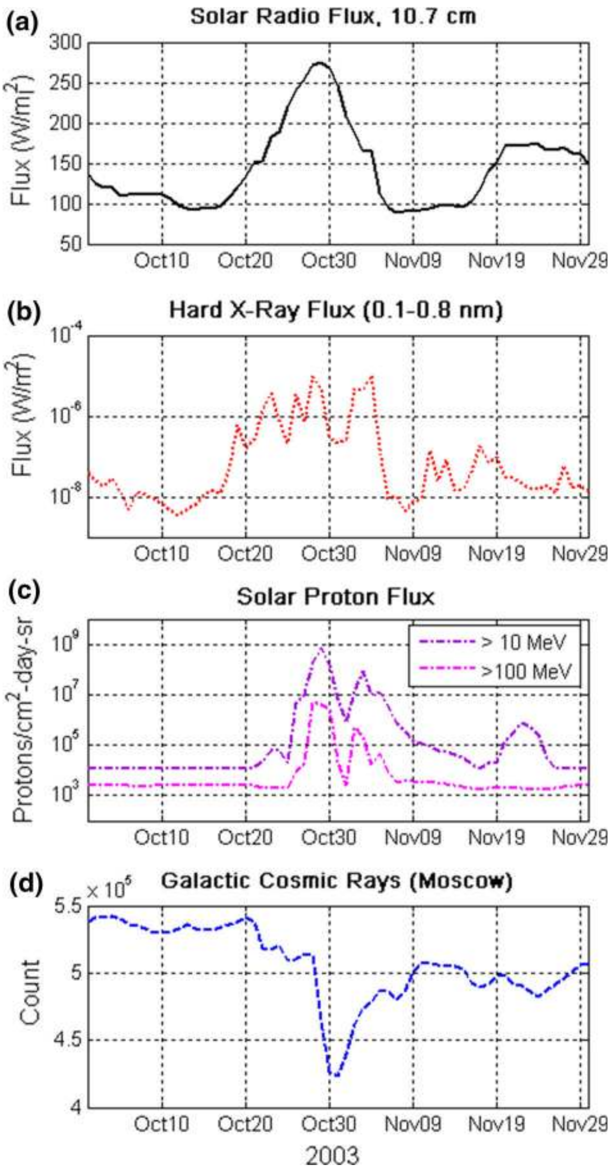

Fig. 5 Time histories of key quantities for the Halloween event of October/November 2003, including (**a**) the 10.7 cm microwave flux, (**b**) the GOES solar X-radiation flux (0.1–0.8 nm wavelength), (**c**) the GOES solar proton flux (in two energy ranges, >10 MeV and >100 MeV, and (**d**) the galactic cosmic ray count (recorded in Moscow). The timing of the maxima in fluxes of X-radiation and solar protons are generally consistent with specific solar events (flares and coronal mass ejections) documented in Lopez et al. (2004)

295 2004) is unprecedented in the era of GOES satellite measurements of hard X-rays. (The
296 GOES sensors were saturated on November 3 during an X-28 class solar flare, and the
297 analysis of that saturation lead to an upgrade in the classification to X-45.) The mean x-ray

Journal : Small 10712 | Dispatch : 5-3-2016 | Pages : 33
Article No. : 9369 | ☐ LE | ☐ TYPESET
MS Code : GEOP-D-15-00044 | ☑ CP | ☑ DISK

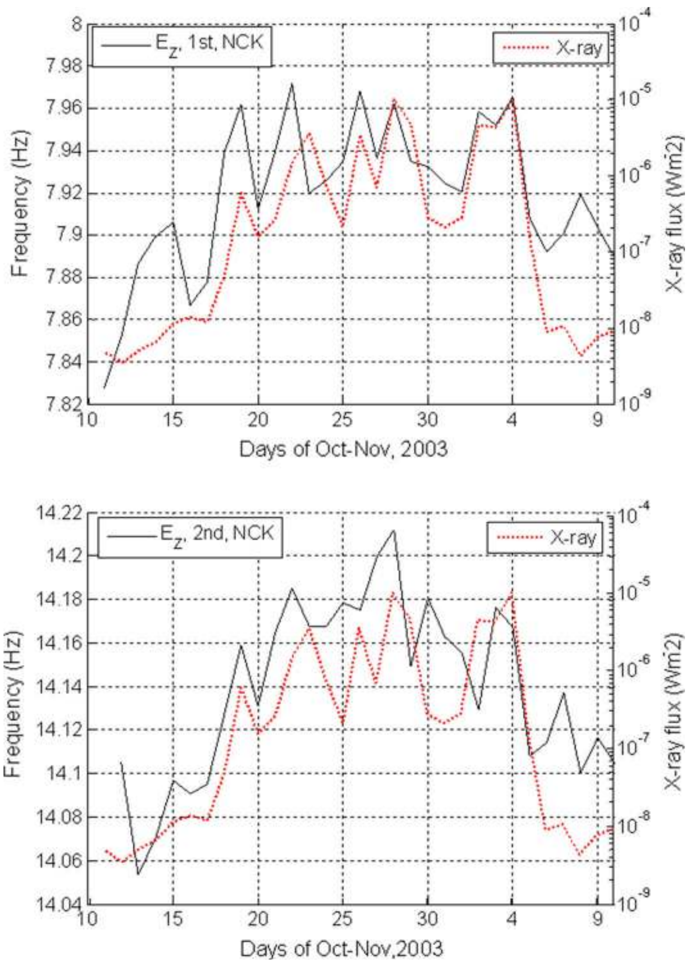

Fig. 6 Simultaneous records of Schumann resonance frequency variations (in Hertz) during the Halloween Event (October/November, 2003) in the first (*top plot*) and second (*bottom plot*) mode of the vertical electric field at Nagycenk (Hungary) Observatory, and the GOES solar X-radiation flux (0.1–0.8 nm wavelength). Note positive correlation of frequency variations and X-ray flux over the substructure of the X-ray record

flux was 2.7×10^{-6} W/m^2 in this period in contrast with the mean level of 1×10^{-8} W/m^2 in the 3 days before and after this strongly disturbed interval. All modal frequencies at all SR stations increased during the days of increased X-ray flux for both the electric and magnetic field components. This organized global behavior is shown by consistent Schumann resonance frequency records at Nagycenk, Hungary (Fig. 6), Mitzpe Ramon, Israel (Fig. 7), Parkfield, California (Fig. 9) and Vernadsky, Antarctica (Fig. 10) that are all well correlated with the GOES satellite measured X-radiation. The magnitudes of the frequency variations, extracted from these various time series records, are summarized in Tables 5, 6, 7 and 8 in the "Appendix". The frequency changes were estimated in the same way as for the perturbed and reference levels for the X-ray flux variations. Within this extended Halloween event, a giant solar proton event also occurred on October 25,

Journal : Small 10712 | Dispatch : 5-3-2016 | Pages : 33
Article No. : 9369 | □ LE | □ TYPESET
MS Code : GEOP-D-15-00044 | ✔ CP | ✔ DISK

7 days after the onset of the marked X-ray activity. The increase of solar proton flux (>10 MeV) was more than four orders of magnitude (10^{-1}–10^{3} protons/(cm^{-2} s^{-1} $sr^{-1)}$ with the maximum value on October 29. The period of increased frequencies was interrupted in the case of the H_{EW} field component for each mode at the Mitzpe Ramon station for some days near the time of peak values of solar proton flux, as shown in Fig. 8 and a sudden decrease in frequency occurred on October 26 and for more than five consecutive days when the solar proton flux still varied by more than two orders of magnitude. Then, the frequencies began to increase again during the bursty X-ray period that persisted until November 4. In this case, the frequency values measured on October 26 and the mean frequency value of October 28–30 are compared as shown for H_{EW} at Mitzpe Ramon in Table 5.

A regression analysis of the frequencies was performed using different combinations of stations, field components, and modes for exactly the same time windows presented in Figs. 6, 7, 8, 9 and 10. Although the time history of the event is lost in the regression analysis, it can be seen in Figs. 11 and 12 that all combinations of frequency values exhibit increasing trends. The increasing trend is especially important in case of the regression analysis for PKD (Northern Hemisphere station) and VND (Southern Hemisphere station) (see the subplots: Fig. 12a, b). This result excludes the possibility of a systematic meridional source motion with respect to these two stations during the event as the 1st magnetic mode is an excellent indicator of the source motion, too (Nickolaenko and Hayakawa 2002). In the latter case, the regression analysis should have shown a decreasing trend. (The frequency of the H_{EW} field component at PKD should be increasing when the source moves away from the observer and simultaneously decreasing at VND when the source approaches it and vice versa). The increasing trend of frequencies for the H_{NS} field component at MR and PKD (see Fig. 11d) also excludes a systematic westward/eastward motion of the sources from day to day during the observed period. The common increasing

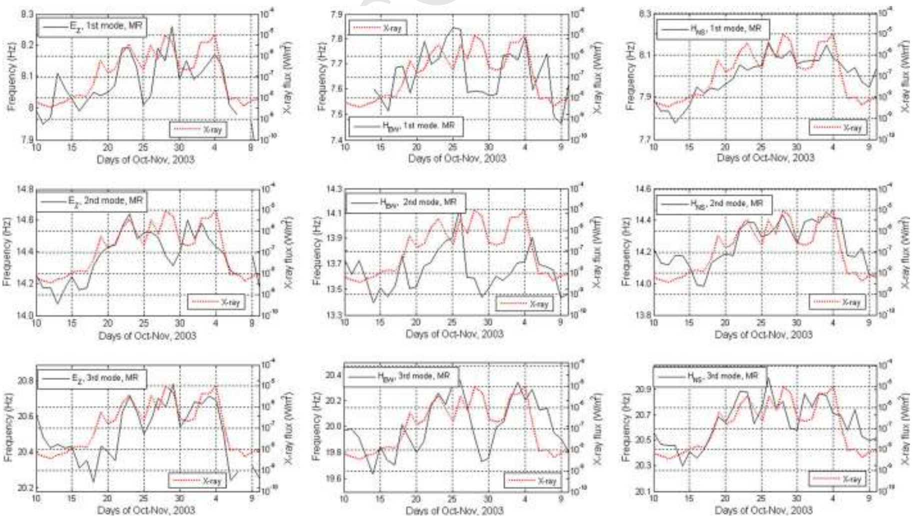

Fig. 7 Simultaneous records of Schumann resonance frequency variations (in Hertz) during the Halloween Event (October/November, 2003) for three field components (E_z, H_{EW} and H_{NS}, running *left* to *right*) and for three modes (running from top to bottom) at Mitzpe Ramon, Israel, and the GOES solar X-radiation flux (0.1–0.8 nm) (*red*, *dashed*, and repeated panel to panel)

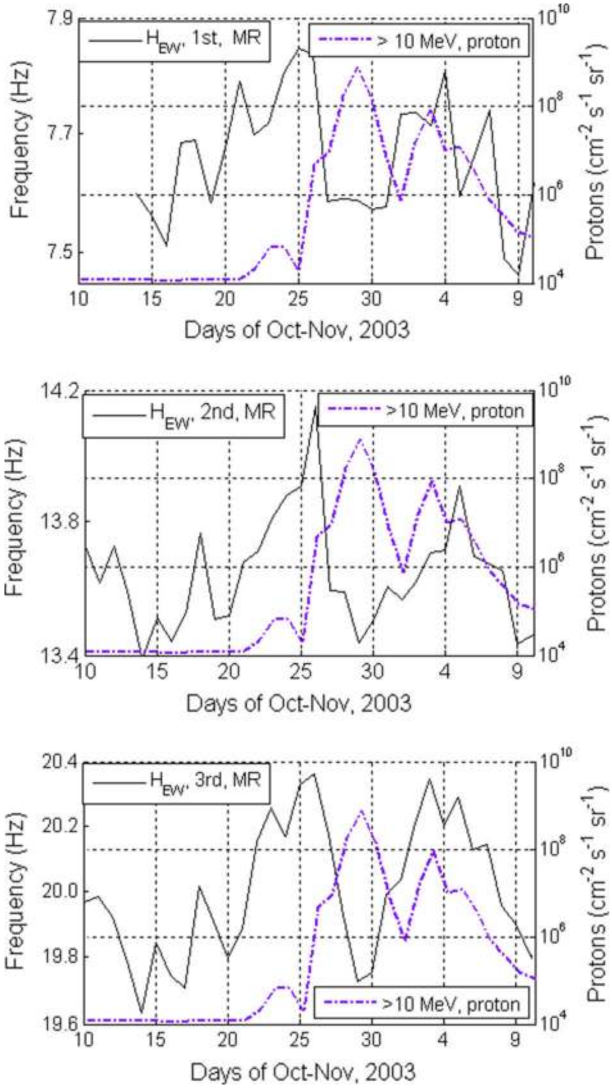

Fig. 8 Simultaneous records of Schumann resonance frequency variations (in Hertz) during the Halloween Event (October/November, 2003) for the H_{EW} component of magnetic field for three resonance modes (from *top* to *bottom*) at Mitzpe Ramon, Israel, and the GOES solar proton flux (>10 MeV) superimposed on each subplot (*dashed*, *purple*, and repeated panel to panel)

trends indicate the ionospheric origin of the frequency variations due to the excess ionization in the upper D-region attributed to the increased background solar X-ray flux by more than two orders of magnitudes during the Halloween event (~2 weeks). Insignificant trends were found only in those cases (subplots Figs. 11c, 12c) when the H_{EW} field component recorded in MR was involved in the regression analysis. The increased frequencies due to the increased X-ray flux were interrupted by a large decrease of frequency during the huge solar proton event discussed as the manifestation of an anisotropic wave

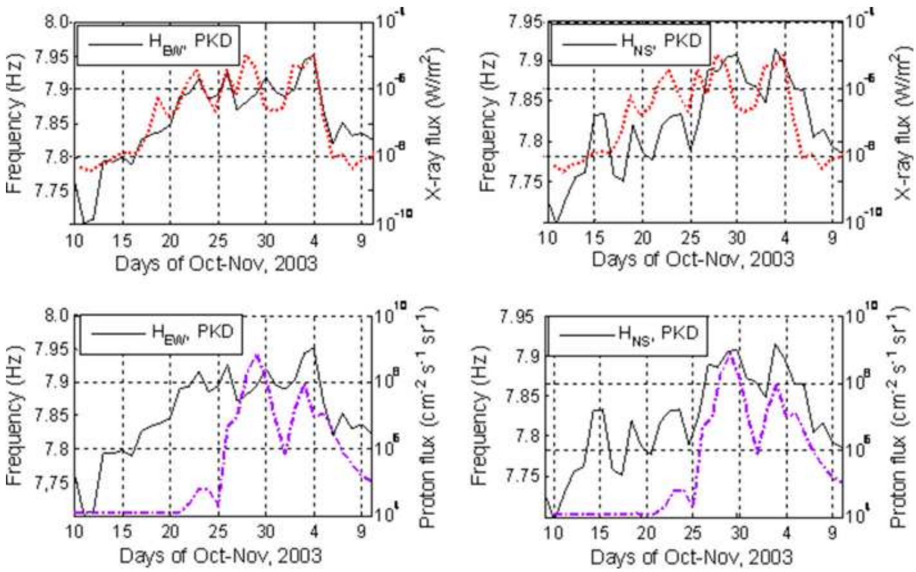

Fig. 9 Simultaneous records of the Schumann resonance frequency variations (in Hertz) during the Halloween Event (October/November, 2003) for the H_{EW} (*left panels*) and H_{NS} (*right panels*) components of magnetic field at Parkfield, CA. Superimposed on the frequency records are the histories of the GOES solar X-radiation flux (0.1–0.8 nm wavelength, *top panels*, *red, dashed*) and the GOES solar proton flux (>10 MeV, *lower panels*, *purple*, *dashed*)

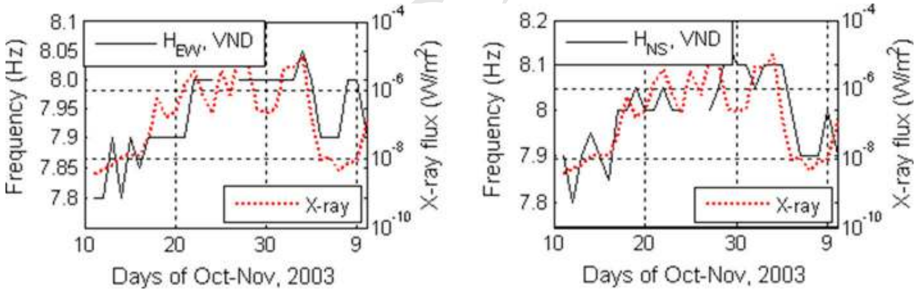

Fig. 10 Simultaneous records of the Schumann resonance frequency variations (in Hertz) during the Halloween event (October/November 2003) for the H_{EW} (*left panels*) and H_{NS} (*right panels*) components of magnetic field at Vernadsky, Antarctica. Superimposed on the frequency records are the histories of the GOES solar X-radiation flux (0.1–0.8 nm wavelength, *red*, *dashed*, and repeated panel to panel)

propagation and shown in Fig. 8. The two effects with the opposite sign of frequency variations canceled each other in the regression analysis. A SO effect might appear in the scatter of frequency values around the regression line due to the day-to-day variability of the global lightning distribution on the timescale of the Halloween event.

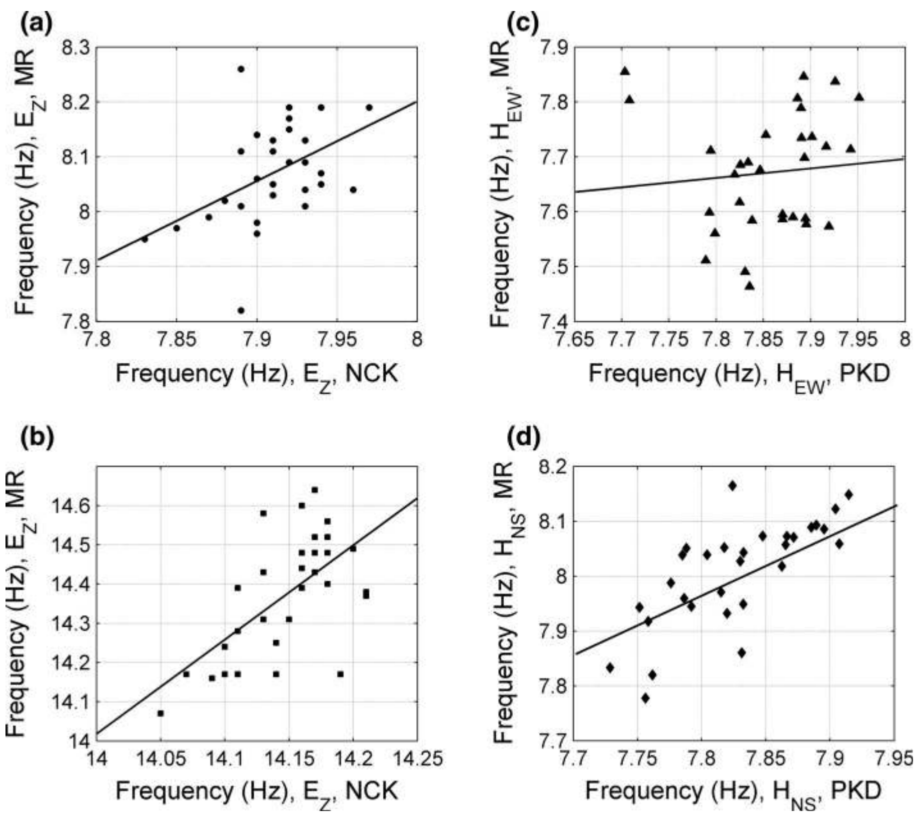

Fig. 11 Regression analysis on simultaneously measured modal frequencies for the different combinations of SR station-pairs **a** NCK–MR, E_Z, 1st mode; **b** NCK–MR; E_Z, 2nd mode; **c** PKD–MR, H_{EW}, 1st mode; **d** PKD–MR, H_{NS}, 1st mode

4.2.2 The Halloween Event: Results on Intensity Variations

Considerable effort has been invested in looking for an intensity response to the unprecedented X-ray increase in the Halloween event. With the knowledge that the dayside of the Earth is the main recipient of the increased X-ray flux from the Sun, the SR intensity observations at Parkfield were separated into daytime and nighttime contributions. The mean intensities during 10 local daytime hours (8–18 h LT) and 10 local nighttime (20–06 h LT) hours were considered to form two separate time series. Figure 13 shows these two contributions for the full 2-month period (October/November 2003) surrounding the Halloween event. As expected, the daytime intensities are systematically greater than the nighttime ones and additionally a small but discernible increase ($\sim$10 %) can be noted during the X-ray forcing, especially in the case of the H_{NS} field component (upper right subplot of Fig. 13). It might be considered as the consequence of the changed cavity properties because the H_{NS} field component is responsive for the east–west propagation paths of ELF waves and the cavity in these low-latitude zonal regions can be influenced only by X-ray variations. The problem is that the natural variability of the SR intensity

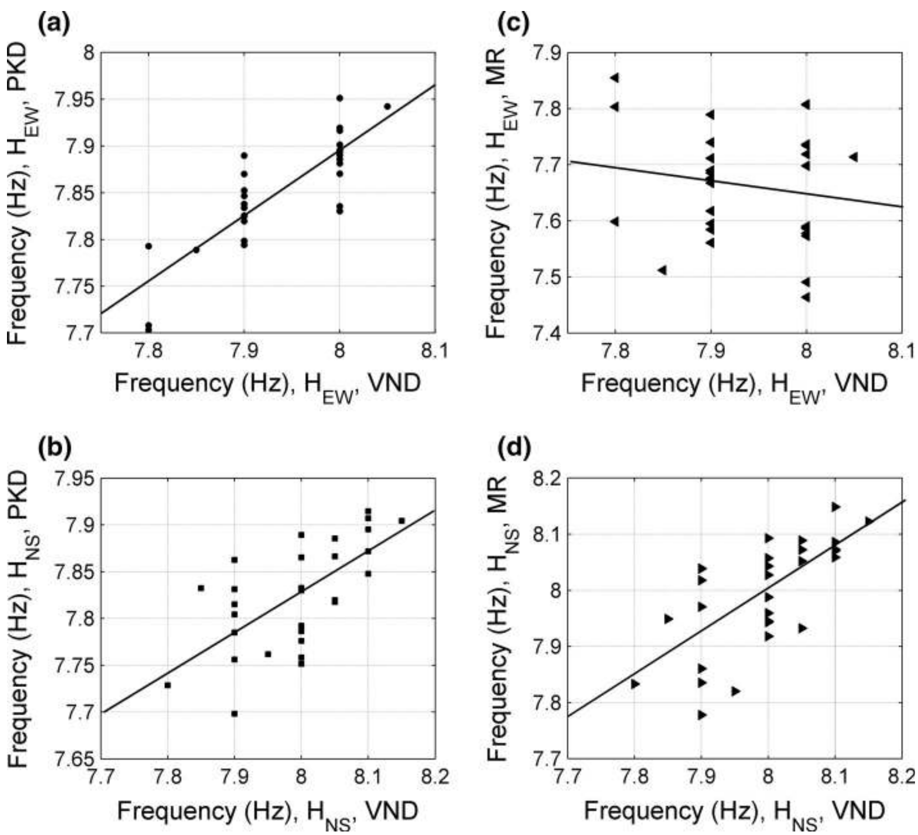

Fig. 12 Regression analysis on simultaneously measured modal frequencies for the different combinations of SR station-pairs **a** VND–PKD, H_{EW}, 1st mode; **b** VND–PKD, H_{NS}, 1st mode; **c** VND–MR, H_{EW}, 1st mode; **d** VND–MR, H_{NS}, 1st mode

competes with the predicted changes due to cavity deformation. This point will be further clarified in the interpretation Sect. 5.

4.2.3 The Halloween Event: Results on Damping

Spectral half-widths given in Hertz (closely related to the reciprocal of the Q factor) were available from the Parkfield station in October–November, 2003. These parameters are characteristic for the damping of the propagating waves in the SR cavity. Figure 14 shows these values for the H_{EW} and H_{NS} field components together with the proton flux variations (upper three subplots) as well as the intensity variation of the E_Z field component available at the Nagycenk Observatory, Hungary (bottom subplot) during October–November days. It can be seen that the damping is slightly increased in the days near the maximum of proton flux and the intensity of E_Z shows a moderate decrease in that time period but the magnitude of the decrease is comparable with the diurnal intensity variations due to changes in the source intensity.

Journal : Small 10712 | Dispatch : 5-3-2016 | Pages : 33
Article No. : 9369 | ☐ LE | ☐ TYPESET
MS Code : GEOP-D-15-00044 | ☑ CP | ☑ DISK

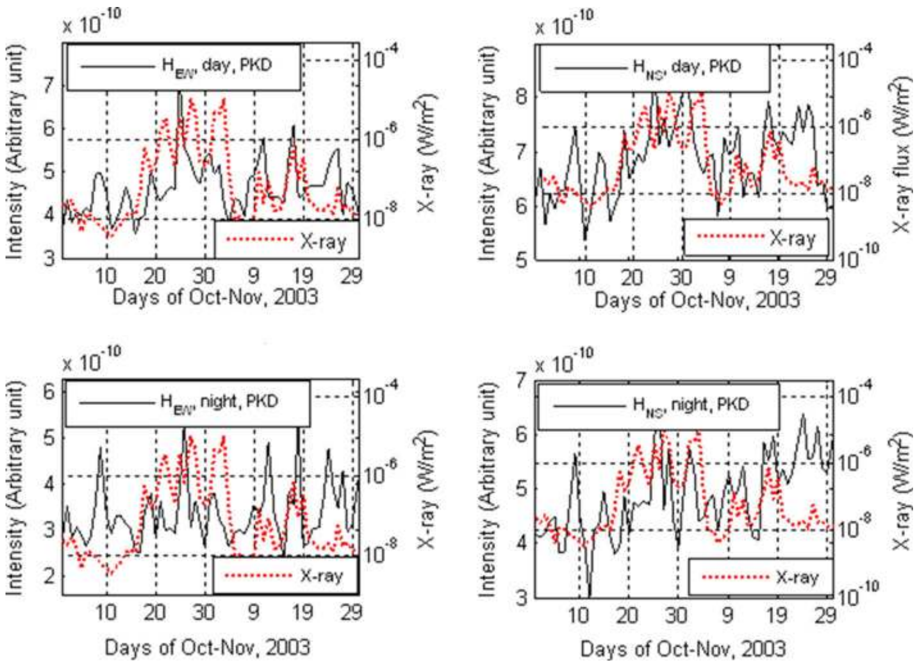

Fig. 13 Simultaneous records of Schumann resonance intensity during the Halloween event (October/November, 2003) at Parkfield, CA for the 2-month interval bracketing the Halloween event. Local daytime records are shown in the *top panels* and local nighttime records in *bottom panels* for both components of magnetic fields (H_{EW} *left*, H_{NS} *right*). Superimposed on the frequency records are the histories of the GOES solar X-radiation flux (0.1–0.8 nm wavelength, *red*, *dashed*, and repeated panel to panel)

5 Discussion

5.1 Interpretation of Results: Frequencies and Q factors

The perturbations to the Earth–ionosphere cavity by ionizing protons and X-radiation are decidedly non-uniform on both short and long timescales, but in keeping with the analytic convenience of earlier work (Sátori et al. 2005), we shall attempt a zeroth-order interpretation of the observations in the context of a uniform cavity. The main observables are Schumann modal frequencies and Q factors. In the context of the uniform knee model (Mushtak and Williams 2002) that is used for the sake of simplicity in the interpretation of observations in this study, the entire cavity response is determined by four physical quantities: two characteristic heights and two conductivity scale heights at the same two altitudes. The approximate nature of this uniform assumption deserves special emphasis in the context of quantitative predictions for the frequency and intensity changes in these energetic solar events. We are confident in the predictions for the *signs* of the frequency changes (consistent with the unanimous agreement among multiple receiving stations within the non-uniform cavity). But no great accuracy is claimed for the magnitudes of the changes, as they are highly dependent on the spectral methods different for nearly all the stations. The use of a more sophisticated day-night model of the cavity and the consistent treatment of time series data from all stations will be needed in future studies toward achieving greater consistency between theory and observation.

Journal : Small 10712 Dispatch : 5-3-2016 Pages : 33
Article No. : 9369 LE TYPESET
MS Code : GEOP-D-15-00044 CP DISK

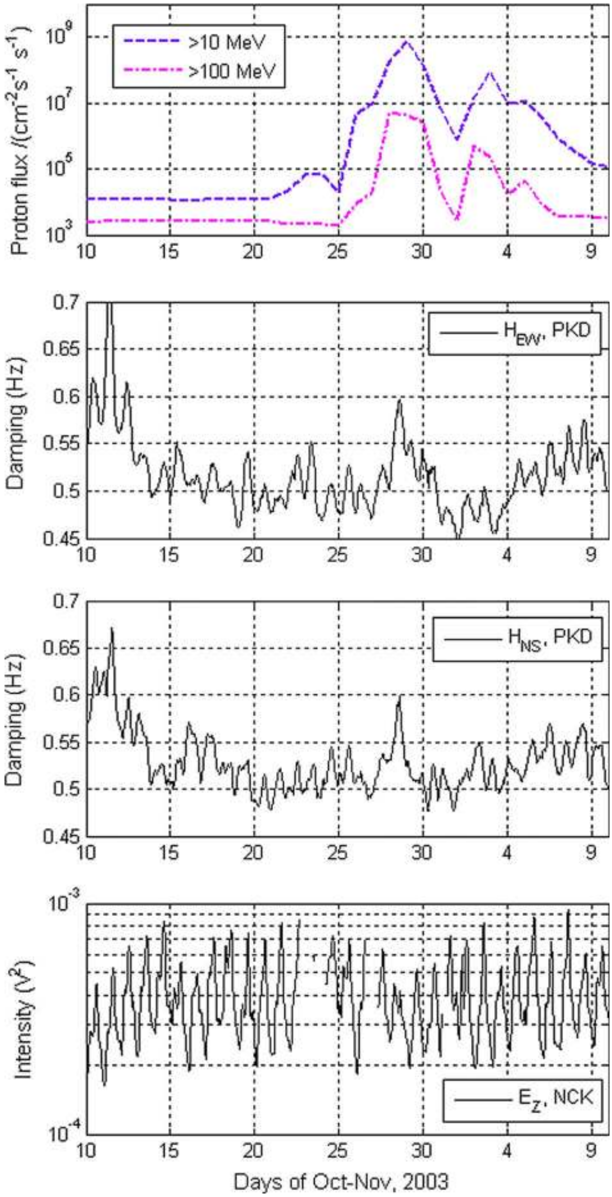

Fig. 14 Simultaneous records of solar proton flux in two energy ranges (*top panel*) and damping parameter for the H_{EW} (*second panel*) and H_{NS} (*third panel*) field component at Parkfield and the SR intensity variation of the E_Z field component (*fourth panel*) at Nagycenk in October–November days, 2003 of the Halloween event

For a fixed Earth circumference, the modal frequencies are physically linked directly with the phase speeds of the waves, and the latter depend on the ratio of the heights. (When the two heights merge at higher frequency (VLF), the phase speed is the speed of light.) Accordingly, the modal frequency is

Journal : Small 10712 Dispatch : 5-3-2016 Pages : 33
Article No. : 9369 LE TYPESET
MS Code : GEOP-D-15-00044 CP DISK

$$f_n \approx f_n^{(0)} \sqrt{\frac{h_{\mathrm{e}}(f_n)}{h_{\mathrm{m}}(f_n)}}, \quad \text{where} \quad f_n^{(0)} \equiv \left(\frac{c}{2\pi a}\right)\sqrt{n(n+1)} \tag{1}$$

The f_n modal frequencies are not exactly the eigenmodal frequencies of the Earth–ionosphere cavity, as they are specified theoretically for a uniform cavity. They are not eigenmodal frequencies due to the overlapping of the neighboring modes in the lossy Earth–ionosphere cavity, and the multiple asymmetries (departures from a uniform cavity) in reality. The observable SR frequencies depend on the cavity properties and on the source–observer distance (Balser and Wagner 1962; Madden and Thompson 1965; Nickolaenko and Hayakawa 2002).

Although it is less well known in the SR community, the SR frequencies also depend on the spectral method employed (Verő et al. 2000; Yang and Pasko 2006; Ondrášková and Ševčík 2014). Using the same time series, Verő et al. (2000) compared SR frequencies computed by FFT and complex demodulation, and Yang and Pasko (2006) determined SR frequencies by Lorentzian fitting and Prony algorithm. Both studies found systematic differences (some tenths of Hz) in the frequency values deduced by different spectral techniques. It is important to note that the station-to-station frequency values can be compared quantitatively if they are determined by the same spectral technique.

The formula for the global quality factor involves the two heights and in addition, the two scale heights of conductivity at the same two altitudes (Nickolaenko and Rabinowicz 1982; Mushtak and Williams 2002). These quantities enter symmetrically in their Q factor dependence.

$$Q_n \equiv \frac{2}{\pi \gamma_n}, \qquad \gamma_n \approx \frac{\varsigma_{\mathrm{e}}^{\mathrm{eff}}(f_n)}{h_{\mathrm{e}}(f_n)} + \frac{\varsigma_{\mathrm{m}}^{\mathrm{eff}}(f_n)}{h_{\mathrm{m}}(f_n)} \tag{2}$$

The incursions of protons and X-rays lead to reductions in the lower and upper characteristic heights, respectively, as discussed in Sect. 3. Reductions in either height alone, with all other quantities remaining constant, lead to reductions in Q factor. In Sátori et al. (2005), the observations showed that for the X-ray response on the solar cycle timescale, both a reduction in upper characteristic height and a reduction in the upper characteristic scale height produced increases in frequency and Q factor consistent with the measured response. In another recent study, Dyrda et al. (2015) document large increases in cavity Q factor associated with a solar flare of short duration. In this study, the separate reduction in lower characteristic height by the energetic proton incursion alone leads to reductions in frequency (shown) and Q factor (not shown) that are broadly consistent with the observed behavior for both the Halloween Day and Bastille Day storms, as well as with earlier observations (and modeling) by Nelson (1967) on solar proton events.

The use of Eqs. (1) and (2) for the interpretation of observations is most appropriate when the changes in cavity properties (heights and scale heights) are globally uniform. With the possible exception of the cavity response to changes in galactic cosmic radiation, this uniform scenario is seldom realized. It is well recognized that the bombardment of the Earth's atmosphere by the X-ray, electron and proton bombardments of the kind considered here is far from globally uniform. The X-radiation comes closest to this idealization, in being quasi-uniform on the sunlit side of the Earth's atmosphere, though the high-latitude penetration will be diminished on account of the near-grazing incidence.

For the Bastille Day event, Table 4 shows that the frequency increase in response to the X-ray event was matched at +0.3 Hz on both magnetic channels. Computations using

Eq. (1), with reference to earlier calculations (Sátori et al. 2005), show that a reduction in the magnetic height h_m from 99 to 92 km, with no change in the electric height h_e would account for the measured change in a uniform waveguide. The observed frequency increase is larger than the one recorded with the same equipment and processing methods at RI in response to the 11-year solar cycle increase in X-radiation documented by Sátori et al. (2005), with a required larger height change by ~2 km. Consistent with this larger overall frequency change is the finding that the variation in X-ray intensity for the Bastille Day event exceeded the 100-fold change over the 11-year solar cycle by about 50 %. This is consistent with the larger frequency increase for the Bastille Day event (+0.3 Hz) than for the solar cycle (+0.2 Hz). Regarding the SR response to the following proton flux later in the Bastille Day event (Fig. 2), the largest frequency decrease is recorded in the E_Z field component (Table 4) and is ~0.8 Hz. Use of Eq. (1) for a uniform model with the assumption that the proton event involves only a change in h_e shows that a height decrease from 52 to 42 km is required. This diminished height is substantially less than the model prediction (28 km) for the Bastille Day event (Ondrášková 2005), and this may be due to our use of a uniform model for interpretation. The evidence in Fig. 1 suggests that protons with energy in the range of 30–100 MeV dominate this modification in ionospheric height in the magnetically unshielded polar regions, and also validates the assumption that only the lower characteristic height is affected by these protons.

For the Halloween event, we consider again the very consistent frequency response at several stations (Figs. 6, 7, 9, 10) to X-radiation on a substantially longer timescale, supporting the global nature of the response. Table 5 ("Appendix") shows a frequency increase of ~0.2 Hz recorded at Mitzpe Ramon for the fundamental mode. This change is comparable to the first SR response (+0.20 Hz) to the change in X-radiation over the solar cycle in Sátori et al. (2005), but it must be remembered that the competing effects of the protons are superimposed on the X-ray contributions for the Halloween event. In the present case, the use of Eq. (1) for a uniform cavity requires a diminishment of h_m from the reference level (Sátori et al. 2005) of 99 to 94 km to account for the measured frequency change, and with no modification of the lower height h_e.

Regarding the frequency response to the proton arrival that peaks up on October 29 in association with the coronal mass ejection (Lopez et al. 2004) as shown in Fig. 8 or the Halloween event, Table 5 ("Appendix") shows a frequency decrease of ~0.2 Hz in the Hew component of magnetic field. Referring again to Eq. (1) shows that this diminishment of frequency will require a drop in the lower height h_e from the reference level of ~52 km (Sátori et al. 2005) to 48 km. This is a rather modest change, and according to the calculations in Fig. 1, which indicates a predominant role of protons with energy not much more than 30 MeV. However, because of the simultaneous occurrence of effects from both protons and X-radiation, serving to dilute the impact of the protons, this interpretation must be treated cautiously.

In pioneering work on this subject, Schlegel and Füllekrug (1999) found increases in daily-averaged Schumann resonance frequencies associated with a collection of nine solar proton events. These observations run counter to both earlier theoretical and experimental results (Madden and Thompson 1965; Nelson 1967), to later observations on the Bastille Day event (Roldugin et al. 2003; De et al. 2010) and other relativistic solar precipitation (Roldugin et al. 1999, 2001), to more recently published results (Zhou and Qiao 2015), and to the results shown in this study for two of the strongest solar proton events on record. Three possible explanations for this apparent discrepancy are suggested. The first is that the events chosen by Schlegel and Füllekrug (1999) involved dominant proton energies not much greater than 1 MeV, and so according to Fig. 1, only the upper characteristic height of the Schumann cavity is affected, consistent with their own theoretical interpretation. Further resolution here will require a more complete look at the proton energy spectra for the selected events. The second reason is that X-radiation in the same events is not considered. In many proton events, the faster moving X-radiation arrives from the Sun ahead of the protons, and produces systematic frequency increases in SR, on both short (Roldugin et al. 2003, 2004; De et al. 2010; Fig. 2 in this study) and long [Sátori et al. (2005)] timescales, with the general interpretation being that only the upper characteristic layer is affected. This explanation is problematic, however, because in general, after an initial relatively short X-ray event, a much long sustained flux of energetic protons is observed (Roldugin et al. 2004; Belov et al. 2005), which one would expect to dominate the X-ray effects and preferentially influence the lower characteristic height. However, it should also be noted that one of the largest solar proton events (October 1989) documented by Schlegel and Füllekrug (1999) was later shown (Belov et al. 2005) to exhibit an elevated flux of X-radiation throughout the two-week-long event. The third reason is related to the second one. These authors had access to SR frequency changes at the Arrival Heights ELF station with only daily resolution. Given the evidence for variable contributions from different species (X-rays, protons and electrons) at shorter timescales than 1 day may lead to aliasing of the results.

Distinct contrasts in the frequency response on magnetic coils oriented east–west and north–south have been documented for both the Halloween Event (most strongly at the Mitzpe Ramon station, as shown in Fig. 7, and less prominently at Parkfield, as shown in Fig. 9) and for the Bastille Day event (on the Rhode Island station, as shown in Fig. 2). The systematic nature of the observed response, namely a substantially larger lowering of frequency in the EW magnetic field relative to the NS field, was shown earlier for the same Bastille Day event by Nickolaenko and Hayakawa (2002, Fig. 6.30), at another ELF station at Karymshino (53°N, 158°E) in Kamchatka. (In additional documentation of the Bastille Day event by Roldugin et al. (2003), De et al. (2010) and Sanfui et al. (2015), only one SR field component is shown so these contrasts in frequency behavior cannot be explored.) Anisotropic effects on phase speeds of Schumann resonance waves can be expected when the polar regions are more strongly affected by ionizing particles than lower latitudes. In all these cases, reductions in modal frequencies are noted, consistent with a greater separation between the two characteristic heights h_e and h_m in Eq. (1), caused primarily by a lowering of h_e relative to h_m. Charged particles electrons and protons will find easier entry into the lower and upper D-regions of the ionosphere along the Earth's magnetic field lines, where the impact on heights will be more dramatic. Global waves propagating meridionally and sampled in the EW component of magnetic field will propagate through both polar regions, whereas zonally propagating waves, sampled in the NS magnetic field, are expected to be less affected by the polar modifications.

In the same manner that solar proton events induce anisotropy in the frequency response for two magnetic field directions, one might expect that pure X-ray bursts might induce anisotropy by affecting the upper characteristic height at low latitudes preferentially relative to the meridional path linking the polar regions. In this scenario, the Hns frequency is expected to increase more strongly than the Hew frequency. Some slight indication of this expectation can be seen in Fig. 2 for the Rhode Island records for the initial X-ray excursion for the Bastille Day event where one can make comparisons for three resonant modes. A search for such an effect in more numerous but weaker X-ray events in Roldugin et al. (2004) does not show any obvious tendency.

Journal : Small 10712 | Dispatch : 5-3-2016 | Pages : 33
Article No. : 9369 | ☐ LE | ☐ TYPESET
MS Code : GEOP-D-15-00044 | ☑ CP | ☑ DISK

5.2 Interpretation of Results: Intensity Variations

The effects of height of the Earth–ionosphere cavity on Schumann resonance intensity have long been recognized (Madden and Thompson 1965; Sentman and Fraser 1991; Schlegel and Füllekrug 1999; Füllekrug et al. 2002; Greifinger et al. 2005). The role of X-radiation and energetic protons in the ionization of D-region altitudes of interest for SR is also well known (Richmond and Venkateswaran 1971; Sentman 1990; Hargreaves 1992; Roldugin et al. 2003, 2004; Ondráškova 2005; Sátori et al. 2005) and has been reviewed in Sect. 3.1. In the context of the analytical treatments for the Earth–ionosphere cavity (Greifinger and Greifinger 1978; Mushtak and Williams 2002; Greifinger et al. 2007), it is essential that the ionizing radiation affect at least one of two characteristic heights to be effective in modifying Schumann resonance intensities. In this context, Williams and Sátori (2007) have emphasized the need for large changes in ionization to enact appreciable changes in the two characteristic heights. The reason for this need is that generally height is logarithmic in conductivity, with the implication that an order of magnitude change in conductivity is needed to enact a change in characteristic height (lower or upper) equal to one scale height. One conductivity scale height ($\sim$5 km) is typically quite small in comparison with typical characteristic heights (50–90 km).

It turns out, however, that for both X-rays and solar proton emission from the Sun, the changes in intensity on record for exceptional events can be several orders of magnitude. Variations in X-ray intensity of two orders of magnitude and more have been documented on both short and long timescales (Belov et al. 2005; Sátori et al. 2005). Documented intensity changes in solar proton events in certain energy ranges can be even more dramatic. For the Bastille Day event, a five-order-of-magnitude increase of proton flux with energy >100 MeV in hourly time resolution has been documented. For the Halloween event, five- and three-order-of-magnitude increases of energetic proton flux with energies of >10 and >100 MeV, respectively, in daily time resolution were exhibited (http://spidr.ngdc.noaa.gov/spidr/). These changes can translate to changes in lower characteristic height amounting to several scale heights.

Greifinger et al. (2005) have made predictions based on the transmission line treatment of SR by Kirillov (1996) and others for changes in SR amplitude as a function of changes in ionospheric height.

The predictive equations for the field response of the three field components (E_r, H_φ and H_θ) to height variations are reproduced below. M_S, which is frequency dependent, is the charge moment of the lightning source, h_e is the lower (capacitive, electric) height and h_m is the upper (inductive, magnetic) height. Parentheticals (S) and (O) refer to heights over the source region and over the observer region, respectively, which were also considered earlier by Madden and Thompson (1965; page 244).

$$E_r(f; S \to O) \sim M_S(f) \frac{h_m(S)}{h_e(S)} \frac{1}{h_e(O)} [U(S \to O)] \tag{3}$$

$$H_\phi(f; S \to O) \sim M_S(f) \frac{h_m(S)}{h_e(S)} \left[\frac{1}{h_m(O)} \frac{\partial U(S \to O)}{\partial \theta} \right] \tag{4}$$

$$H_\theta(f; S \to O) \sim M_S(f) \frac{h_m(S)}{h_e(S)} \left[\frac{1}{h_m(O)} \frac{\partial U(S \to O)}{\partial \phi} \right] \tag{5}$$

The effect of wave propagation between source *S* and observer *O* represented by some formula *U* representing the electric field response to point source excitation along the great circle path between source (*S*) and observer (*O*). For a uniform cavity (no lateral variations in heights of either kind) *U* is analytic, is the voltage on the transmission line represented as the product of the local electric field and the local constant 'electric' height, and can be found in works by Wait (1962); Huang et al. (1999), Nickolaenko and Hayakawa (2002) and Sátori et al. (2009). U' is the magnetic field and is obtained analytically from *U* by application of Faraday's Law. For the non-uniform cavity, one no longer has an analytical form, and hence the justification for the use of the symbolic forms *U* and U' above. But despite the loss of the analytic form, the scaling of the fields with waveguide heights is known from the transmission line/telegraph equation analogy. We assume here that during the days of solar events in question, that the distance-dependent variations of *U* and U' are invariant with time as the source–observer geometries are not appreciably modified from day to day, and so we do not need to know these *U*, *U'* quantities in making our predictions for field/intensity changes.

Simple assumptions are made here about height variations in X-ray and solar proton events to see what amplitude changes can be expected. As noted earlier, X-rays in the wavelength region 0.1–0.8 nm have a 'Chapman layer' in the vicinity of 90 km height (Richmond and Venkateswaran 1971). For the solar X-ray enhancement amounting to two orders of magnitude, and a conductivity increase of about one order of magnitude, the treatment in Sátori et al. (2005) is repeated. This involves a height decrease (at 8 Hz) by about one scale height from $h_m = 99$ km to $h_m' = 94$ km. It should be noted here, however, that the decrease in lower characteristic height consistent with the observed frequency change for the uniform model is substantially less than the model prediction (42 vs. 28 km). This diluted result is consistent with the realization that the big height change is confined to the polar region, where the protons are the guided by the Earth's magnetic field there where the majority of the Earth's magnetic field lines enter and exit. Given these estimates for original and perturbed characteristic heights for the two influences of incident X-rays and protons, the equations can be used to estimate percentage changes in field amplitudes. The results of these simple calculations are included in Tables 2 and 3 below, one each for the electric and the magnetic field. Each Table provides estimates for the percentage change in field amplitude for each of two ionization processes (X-rays and protons) and for each of two observer locations (one mid-latitude and one high latitude). Here, we are assuming unperturbed heights $h_e = 52$ km and $h_m = 99$ km, following Sátori et al. (2005) and perturbed heights of $h_e = 42$ km and $h_m = 94$ km. (In this context, it is noteworthy that Ondrášková (2005) estimated a decrease in h_e to 28 km in modeling work on the Bastille Day event.) The impact on h_e at low latitudes is ignored because of magnetic shielding of the protons by the geomagnetic field.

In the case of predictions for X-ray effects, the same percentage variations of h_m (*S*) and $h_m(O)$ can cancel the X-ray effect in the amplitude of the field components. The amplitude decreases (−5 %) if only $h_m(S)$ decreases and the amplitude increases (+5 %) if only $h_m(O)$ decreases. (The intensity changes in percent will be approximately twice these values, namely if the relative amplitude variation is $1 \rightarrow 1.05$ then the relative intensity variation is $1^2 \rightarrow 1.05^2 = 1.1025$, that is ∼10 %.) In general both $h_m(S)$ and $h_m(O)$ vary simultaneously, but with different magnitudes. The symbolic equations enable us to make estimates for a non-uniform cavity, too, in the case of solar X-radiation if the source (S) and the observer (O) are on the different (sunlit or dark) sides of the cavity. Therefore, in Table 2 and 3 for the X-ray variations, a maximum percentage range of (−5 %)–(0 %) is given for SR electric field as well as (−5 %)–(+5 %) for SR magnetic field at 8 Hz.

Journal : Small 10712 Dispatch : 5-3-2016 Pages : 33
Article No. : 9369 LE TYPESET
MS Code : GEOP-D-15-00044 CP DISK

Table 2 Predicted amplitude changes for Schumann resonance electric field (at 8 Hz), based on the symbolic Eq. (3)

	Mid-latitude observer	High-latitude observer
X-radiation	(−5 %)–(0 %)	(−5 %)–(0 %)
Proton	0 %	+19 %

The global lightning source is assumed to predominate at low latitude

Table 3 Predicted amplitude changes for Schumann resonance magnetic field (at 8 Hz), based on the symbolic Eqs. (4) and (5)

	Mid-latitude observer	High-latitude observer
X-radiation	(−5 %)–(+5 %)	(−5 %)–(+5 %)
Proton	0 %	+11 %

The global lightning source is assumed to predominate at low latitude

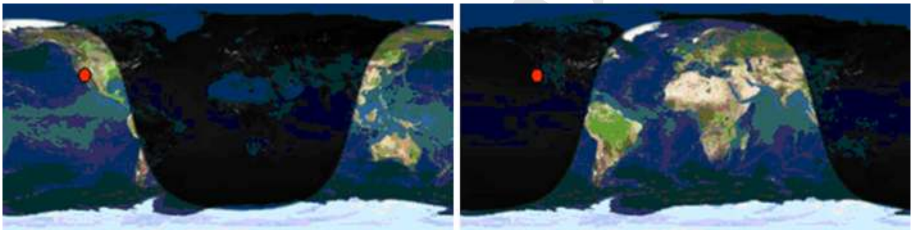

Fig. 15 Sunlit and *dark side* of the Earth when the Parkfield SR station (indicated with *red dot*) is on the dayside at 15 h LT (*left*) and on the nightside at 03 h LT (*right*)

Parkfield is in a special geographical position as shown in Fig. 15. There are several local daytime hours when the main tropical chimney regions are mostly under nighttime conditions during the Halloween event, and the X-ray effect on $h_m(S)$ can be neglected while $h_m(O)$ decreases. This can explain why the magnetic field intensity increases at Parkfield in local daytime hours during the days of the Halloween event (see Fig. 13). With the exception of the high-latitude observer, for which localized effects on amplitude are dominant, the predicted changes in amplitude for low-to-mid-latitude stations are quite modest at only a few percent. At high latitude, the expectation for a large positive amplitude effect is dependent on a decrease in h_e over the observer for the electric field prediction. It means ~19 % increase of E_Z amplitude if $h_e(O)$ changes from 52 to 42 km. It can also be supposed that protons with smaller energies (<3 MeV, see Fig. 1) can influence $h_m(O)$, too, and consequently the magnetic field components can also increase. For example if $h_m(O)$ changes from 99 to 88 km, this means an ~11 % increase in the magnetic amplitudes. It can be stated that the increase of the field amplitudes in the polar region is highly dependent on the energy of the incoming protons (charged particles).

A search for SR intensity changes at mid-latitude station associated with the Bastille Day event (Figs. 3 and 4) West Greenwich, Rhode Island, was shown earlier in Sect. 4, no conspicuous evidence was found and a ~10 % intensity increase related to the bursty X-ray period of the Halloween event was identified in the magnetic field component at Parkfield, but only in the daytime hours and mainly for the H_{NS} field component (see Fig. 13). An intensity decrease of some ten percent appeared in the vertical electric field component at Nagycenk (see Fig. 14) during the quasi-simultaneous episodes of the energetic proton flux and the main depression of the huge Forbush-decrease. The latter event can result in an increase of the $h_e(O)$ and consequently an additional decrease of E_Z due to the decreased cosmic ray ionization with the Forbush-decrease (the first equation in the set of three above). However, the increased damping corresponds to an expected decrease of the Q factor at PKD, contrary to the predictions based on the analytical expression for Q factor. So the uniform model seems inadequate to describe this complicated condition. We did not make model predictions for the damping parameter for the results shown in Fig. 14.

These results are consistent with the predictions for amplitude changes in Tables 2 and 3 for the electric and magnetic field, together with the competition from the natural variability of the intensity which amounts to tens of percent on these relatively short timescales.

These findings are also consistent with a host of earlier published results at mid-latitude stations. For example, Sentman (1996) found no measureable response in SR intensity to large solar storms in the fall of 1989 [the same storms also investigated by Schlegel and Füllekrug (1999) at a high-latitude site] at two mid-latitude stations in California and Australia. Likewise, Roldugin et al. (1999) found no substantial response of the SR amplitude to solar proton events. Roldugin et al. (2001) reported a mixture of results for four solar events in the 1997–1998 time frame. In two cases, decreases of the order of tens of percent in magnetic amplitude were noted, in a third a weak decrease of amplitude and in the fourth no change was detected. The negative signs of the observed changes are also possible in accordance with the predictions in Table 3 but the magnitudes are on the high side, and questions remain about the reality of the physical linkages, given the natural variability. In a still later analysis pertaining to the Bastille Day event, Roldugin et al. (2004) reported: "Neither in Lovozero (68°N, 35°E) nor in Karymshino (53°N, 158°E) any appreciable effect (in magnetic amplitude) is found in any components and modes."

Regarding the situation at high latitude, it is important to note the predictions for magnetic amplitude for the observer at high latitude where the height change is local to that location (the second equation in the set of three above). The magnetic amplitude change is appreciable only if the upper characteristic height h_m is reduced, as noted above. This prediction is consistent with the inconspicuous change in the Vernadsky magnetic intensity at the time of the large proton flux for the Halloween event. For solar protons, we now have abundant evidence that it is the lower height that is affected, not the upper one. The remaining puzzle pertains to the daily mean amplitude increases up to a few tens of percent at Arrival Heights, another high-latitude station, reported by Schlegel and Füllekrug (1999). This would suggest that the h_m values are reduced in keeping with their theoretical interpretation, but not in keeping with the evidence that energetic protons are more likely to lower the h_e values.

5.3 Similarities on the Longer Timescale of the 11-year Solar Cycle

Part of the motivation for investigating the effects of energetic solar emissions on short timescales came from the earlier analysis on the 11-year solar cycle timescale (Sátori et al. 2005). In that work, it was shown that a two-order-of-magnitude increase in hard X-radiation

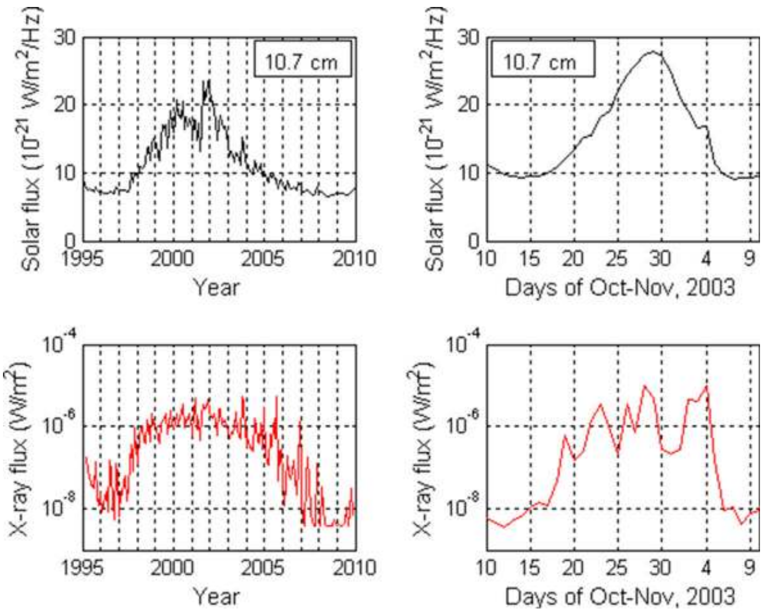

Fig. 16 Flux comparisons on long (11-year solar cycle, *left panel*) and short (~2-week period of 'Halloween' event in October/November, 2003, *right panel*). *Upper plots* represent 10.7 cm radiation flux. *Lower plots* show GOES solar X-radiation (0.1–0.8 nm wavelength) fluxes. The variations in both fluxes are of comparable magnitude on these two quite different timescales

at solar maximum was responsible for a worldwide increase in Schumann resonance modal frequencies. Now that the Halloween event has been explored on a timescale intermediate between the single-day Bastille Event and the 11-year solar cycle, we are now equipped to address the evidence for a timescale independence of the SR X-ray response. Figure 16 compares records of 10.7 cm radiation and sustained X-radiation from the Sun for the 11-year solar cycle on the left and the Halloween event on the right. The 10.7 cm solar radiation is generally used as an indication of solar EUV radiation which is the main ionization source of the upper D-region in daytime. In this depiction, the time history of the Halloween event appears as a miniature version of the solar cycle, though with slightly elevated radiation levels in comparison with the solar cycle. The SR frequency variations follow most closely the time history of the bursty period of X-radiation of more than two orders of magnitude of flux changes as shown in Figs. 6, 7, 9 and 10. The frequency variations do not run parallel with the ~threefold flux changes in the 10.7 cm solar radiation (Williams and Sátori 2007). The systematic and conspicuous positive SR frequency response to X-radiation during the Halloween event has been documented in Figs. 6, 7, 9 and 10 and a similar response to X-radiation on much shorter timescale in the Bastille Day event in Fig. 2. Yet another short term X-ray event was documented in Sátori et al. (2005). Now the SR responses can be assembled for comparison in Tables 4, 5, 6, 7 and 8 in the "Appendix". The sign of the frequency variations can be compared and the magnitudes, too, if the frequencies were determined by the same spectral technique like as at RI and in MR. Here, it is seen that the frequency increases for the 1st SR mode are ordered by the magnitude of the X-radiation flux, independent of the timescale over which the event occurs.

When the records of energetic protons are considered on the widely different timescales of the Halloween event and the 11-year solar cycle, less similarity is apparent. The duty cycle of the protons for the Halloween event is substantially larger than for the solar cycle, with more than half of the overall period of enhanced X-radiation also exhibiting proton enhancements (Fig. 5). On the latter timescale, the general incidence of energetic protons follow the solar cycle and with a rough two-order-of-magnitude change, but the proton flux is highly episodic (Feynman et al. 1990) by comparison and in marked contrast with the quasi-steady variation in the background X-radiation (Veronig et al. 2004) also shown in Fig. 16. The search for an explanation of the sustained enhancement of SR magnetic intensity near solar maximum at the high-latitude station at Vernadsky (Antarctica) arose in this context (Williams et al. 2014). It was also noticed that independent estimates of ionospheric height on a global basis showed a noticeable reduction sustained in time at higher latitude (Toledo-Redondo et al. 2012). The impact of local height changes on SR amplitude was first noted by Madden and Thompson (1965, page 244) but that has since been quantified (Greifinger et al. 2005) with the Eqs. (3) to (5) by the local observer height. A key point in the interpretation of Eq. (4) is that no appreciable increase in amplitude will be manifest at the high-latitude station unless the upper (magnetic) magnetic height is lowered. Yet much evidence has accrued in this study that protons will affect primarily the lower characteristic height there, and indeed, little change in magnetic intensity was noted at Vernadsky (not shown) in response to the energetic protons in the Halloween event. But returning to the solar cycle timescale, if 50 keV electrons are available, Fig. 1 shows that they are most likely to affect the upper characteristic height and on the basis of Eqs. (4) and (5) lead to an enhanced amplitude at solar maximum. Recent discussions (D. Baker, B. Blake and H. Spence, personal communication, December 2014) indicate that such energetic electrons are available from the Earth's inner radiation belt and may be the main players in modulating the SR intensity at Vernadsky over the 11-year solar cycle. This suggestion is currently under further investigation.

6 Conclusions

The main conclusions to be drawn from this work are as follows:

1. Generally speaking, X-rays with wavelengths in the 0.1–0.8 nm range affect the upper characteristic height and solar protons primarily the lower characteristic height of the SR cavity. This result is already well known but is strongly substantiated by results shown here, and the unanimous multiple-station documentation assures the global nature of the phenomena. The linkage with specific altitudes of the ionosphere is consistent with independently published results on penetration depth versus particle energy.
2. Time-resolved frequency variations are essential in diagnosing independent ionizing effects of X-rays and energetic protons on the Earth–ionosphere cavity.
3. The effect of X-radiation on SR frequency increase is not monotonic with X-ray flux and this is probably due to the overlapping effects of the protons that typically force the phase speeds of ELF waves and the attendant modal frequencies in the opposite direction.
4. The impact of charged particle events, most notably the energetic proton events on short timescales, is predominant in polar regions. As a consequence, ELF propagation paths in the meridional direction are more strongly affected than those in the zonal direction. The larger frequency decreases in the east–west magnetic field components compared to the north–south components is consistent with this physical picture.
5. In response to solar events, the SR response in frequency is most conspicuous and in amplitude least conspicuous (consistent with earlier work by Williams and Sátori 2007).

6. The inconspicuous response of SR amplitude/intensity to the most energetic solar events on record is consistent with theoretical considerations and provides additional indirect evidence that the SR intensity is primarily a record of the lightning activity within the Earth–ionosphere cavity. This finding provides additional encouragement to make use of the natural framework of SR to monitor the global lightning activity in absolute units (Williams and Mareev 2014).

Future analyses of major perturbations of the SR will benefit from the use of a cavity model with both day–night and polar asymmetry, and a common processing of all receiver data sets for the same modal frequencies.

Acknowledgments Discussions with Dan Baker, Anatoly Belov, Bern Blake, Steve Cummer, Barbara Emery, Martin Füllekrug, István Lemperger, Adriena Ondrášková, Steve Park, Craig Rodger, Valentin Roldugin, Harlan Spence and Rob Steenburgh are greatly appreciated. Alexander Melnikov provided major assistance with the organization of the Parkfield and Mitzpe Ramon data in early stages. The authors are thankful to the National Antarctic Scientific Center of Ukraine, Ministry of Education and Science of Ukraine for providing the ELF data recorded at the Ukrainian Antarctic Station "Academic Vernadsky". The contribution of Earle Williams to this study was funded by the Hungarian Academy of Sciences as part of a Visiting Fellowship to the Research Centre for Astronomy and Earth Sciences, Geodetic and Geophysical Institute in Sopron. The contribution of Gabriella Sátori was supported by the National Research, Development and Innovation Office, Hungary—NKFIH, K115836.

Appendix

Tables of Modal Frequency Variations in Response to Specific Solar Events

See Tables 4, 5, 6, 7 and 8.

Table 4 Schumann resonance modal frequency changes at West Greenwich, Rhode Island, for the Bastille Day event: July 14, 2000

Mode number	RI, E_Z		RI, H_{EW}		RI, H_{NS}	
	X-ray burst (Hz)	Proton flare (Hz)	X-ray burst (Hz)	Proton flare (Hz)	X-ray burst (Hz)	Proton flare (Hz)
1st mode	+0.2	−0.8	+0.3	−0.5	+0.3	−0.3
2nd mode	+0.3	−1.0	+0.5	−1.0	+0.5	−1.0
3rd mode	+0.5	−1.2	+0.5	−1.0	+0.7	−1.2

Table 5 Schumann resonance modal frequency changes at Mitzpe Ramon, Israel, for the Halloween Event: October–November, 2003

Mode number	MR, E_Z	MR, H_{EW}		MR, H_{NS}
	X-ray (Hz)	X-ray (Hz)	Proton flare (Hz)	X-ray (Hz)
1st mode	+0.2	+0.2z	−0.2	+0.2
2nd mode	+0.3	+0.6	−0.6	+0.4
3rd mode	+0.4	+0.5	−0.5	+0.5

Journal : Small 10712 Dispatch : 5-3-2016 Pages : 33
Article No. : 9369 ☐ LE ☐ TYPESET
MS Code : GEOP-D-15-00044 ☑ CP ☑ DISK

Table 6 First mode Schumann resonance frequency changes at Parkfield, California, for the Halloween Event: October–November, 2003

Mode number	PKD, H_{EW} X-ray (Hz)	PKD, H_{NS} X-ray (Hz)
1st mode	+0.1	+0.1

Table 7 First mode Schumann resonance frequency changes at Vernadsky, Antarctica, for the Halloween Event: October–November, 2003

Mode number	VND, H_{EW} X-ray (Hz)	VND, H_{NS} X-ray (Hz)
1st mode	+0.1	+0.1

Table 8 Schumann resonance modal frequency changes at Nagycenk Observatory (Hungary) for the Halloween Event: October–November, 2003

Mode number	NCK, E_Z X-ray (Hz)
1st mode	+0.1
2nd mode	+0.1

References

Baker DN, Kanekal SG, Li X, Monk SP, Goldstein J, Burch JL (2004) An extreme distortion of the Van Allen belt arising from the Halloween solar storm in 2003. Nature 432:878–881

Balser M, Wagner C (1962) On frequency variations of the Earth–ionosphere cavity modes. J Geophys Res 67:4081–4083

Belov A, Garcia H, Kurt V, Mavromichalaki E (2005) Proton events and X-ray flares in the last three solar cycles. Cosm Res 43:165–178

Bieber JW, Dröge W, Evenson PA, Pyle R (2002) Energetic particle observations during the 2000 July 14 solar event. Astrophys J 567:622–634

Brasseur G, Solomon S (1986) Aeronomy of the middle atmosphere, Second Edition edn. D. Reidel Publishing Company, Dordrecht/Boston/Lancaster

Chapman FW, Jones DL (1964) Earth–ionosphere cavity resonances and the propagation of extremely low frequency radio waves. Nature 177:930–933

De SS, De BK, Bandyopadhyay B, Paul S, Haldar DK, Barui S (2010) Studies on the shift in the frequency of the first Schumann resonance mode during a solar proton event. Atmos Res 72:829–836

Dyrda M, Kulak A, Mlynarczyk J, Ostrowski M (2015) Novel analysis of a sudden ionospheric disturbance using Schumann resonance measurements. J Geophys Res Space Phys 120:2255–2262. doi:10.1002/2014JA020854

Feynman J, Armstrong TP, Dao-Gibner L, Silverman S (1990) New interplanetary proton fluence model. J Spacecr 27:403–410

Füllekrug M (1994) Schumann-Resonanzen in den Magnetifeld-Komponenten, Doctoral dissertation, University of Göttingen, Germany

Füllekrug M, Fraser-Smith AC, Schlegel K (2002) Global ionospheric D-layer height monitoring. Europhys Lett 59:626–629

Journal : Small 10712 Dispatch : 5-3-2016 Pages : 33
Article No. : 9369 LE TYPESET
MS Code : GEOP-D-15-00044 CP DISK

Getselev V, Okhlopkov VP, Podzolko MV (2006) Solar cosmic ray proton fluxes in the Earth's orbit. In: Physics of auroral phenomena, proceedings of the XXIX annual seminar, apatity. Kola Science Centre, Russian Academy of Science, pp 179–182

Greifinger C, Greifinger P (1978) Approximate method for determining ELF eigenvalues in the Earth–ionosphere waveguide. Radio Sci 13:831–837

Greifinger P, Mushtak V, Williams E (2005) The lower characteristic ELF altitude of the Earth–ionosphere waveguide: Schumann resonance observations and aeronomical estimates. In: 6th international symposium on electromagnetic compatibility and electromagnetic ecology, St. Petersburg State Electrotechnical University

Greifinger PS, Mushtak VC, Williams ER (2007) On modeling the lower characteristic ELF altitude from aeronomical data. Radio Sci 42:RS2S12. doi:10.1029/2006RS003500

Hargreaves JK (1992) The solar-terrestrial environment. Cambridge University Press, Cambridge

Kirillov VV (1996) Two-dimensional theory of ELF electromagnetic wave propagation in the Earth–ionosphere waveguide channel. Radiophys Quantum Electron 39:737–743

Kulak A, Mlynarczyk J (2013) ELF propagation parameters for the ground-ionosphere waveguide with finite ground conductivity. IEEE Trans Antennas Propag 61:2269–2275

Kulak A, Kubisz J, Michalec A, Ziba S, Nieckarz Z (2003) Solar variation in extremely low propagation parameters: 2. Observations of Schumann resonances and computation of the ELF attenuation parameter. J Geophys Res 108(A7):1271

Kulak A, Mlynarczyk J, Zieba S, Micek S, Niecharz Z (2006) Studies of ELF propagation in the spherical shell cavity using a field decomposition method based on asymmetry of Schumann

Le G, Han Y, Zhang Y (2007) A comparative analysis of two solar proton events. Chin Sci Bull 52:47–51

Lopez RE, Baker DN, Allen J (2004) Sun unleashes Halloween storm. EOS 85:105–108

Madden T, Thompson W (1965) Low-frequency electromagnetic oscillations of the Earth–ionosphere cavity. Rev Geophys 3:211–254

Mushtak VC, Williams ER (2002) ELF propagation parameters for uniform models of the Earth–ionosphere waveguide. J Atmos Sol Terr Phys 64:1989–2001

Nelson PH (1967) Ionospheric perturbations and Schumann resonance data. Project NR-371-401, Geophysics Laboratory, Massachusetts Institute of Technology, Cambridge, MA

Nickolaenko AP (1997) Modern aspects of Schumann resonance studies. J Atmos Terr Phys 59:805–816

Nickolaenko AP, Hayakawa M (2002) Resonances in the Earth–ionosphere cavity. Kluwer Academic Publisher, Dordrecht, London

Nickolaenko AP, Hayakawa M (2014) Schumann resonance for tyros: essentials of global electromagnetic resonance in the Earth–ionosphere cavity. Springer, Tokyo/Heidelberg/New York/Dordrecht/London

Nickolaenko AP, Rabinowicz LM (1982) Possible global electromagnetic resonances on the planets of Solar system. Space Res XX(1):82–88, 1982 (Trans Kosmicheskie Issledovaniya 20(1):82–88, Jan–Feb

Nickolaenko AP, Kudintseva IG, Pechony O, Hayakawa M, Hobara Y, Tanaka YT (2012) The effect of a gamma ray flare on Schumann resonances. Ann Geophys 30:1321–1329

Ondrášková A (2005) The D-region ion composition and electron density response to strong solar proton events (model simulations). Adv Space Res 35:440–444

Ondrášková A, Ševčik S (2014) The determination of Schumann resonance mode frequencies using iterative procedure of complex demodulation. Contrib Geophys Geodesy 44(4):313–328

Ondrášková A, Krivolutsky A, Laštovička J (2003) Changes of the neutral and ionized composition in the D-region after solar proton event in October 1989 (model simulations). Adv Space Res 31:2169–2176

Ondrášková A, Ševčik S, Kostecky P (2011) Decrease of Schumann resonance frequencies and changes in the effective lightning areas toward the solar cycle minimum of 2008–2009. J Atmos Solar Terr Phys 73:534–543

Palmer DM et al (2005) Gamma ray observations of a giant flare from the Magnetar SGR 1806–20. Nature 434(1):107–1109

Price C, Mushtak V (2001) The impact of the August 27, 1998, γ-ray burst on Schumann resonances. J Atmos Sol Terr Phys 63:1043–1047

Rabinowicz LM, Shvets AV, Nickolaenko AP (2008) Polar non-uniformity of ionosphere related to solar proton events. Telecommun Radio Eng 67(5):413–435

Rees MH (1989) Physics and chemistry of the upper atmosphere, 1st edn. Cambridge University Press, Cambridge

Reid GC (1986) Solar energetic particles and their effects on the terrestrial environment. In: The physics of the sun. Elsevier

Richardson JD, Wang C, Paularina KI (2001) The solar wind: from solar minimum to maximum. Adv Space Res 27:471–479

Journal : Small 10712 | Dispatch : 5-3-2016 | Pages : 33
Article No. : 9369 | ☐ LE | ☐ TYPESET
MS Code : GEOP-D-15-00044 | ☑ CP | ☑ DISK

Richmond AD, Venkateswaran SV (1971) Geomagnetic crochets and associated ionosphere current systems. Radio Sci 6:139–164

Roldugin VC, Maltsev YP, Vasiljev AN, Vashenyuk EV (1999) Changes of the first resonance frequency during relativistic solar proton precipitation in the 6 November 1997 event. Ann Geophys 17:1293–1297

Roldugin VC, Maltsev YP, Petrova GA, Vasiljev AN (2001) Decrease of the first Schumann resonance frequency during solar proton events. J Geophys Res 106:18555–18562

Roldugin VC, Maltsev YP, Vasiljev AN, Shvets AV, Nickolaenko AP (2003) Changes of Schumann resonance parameters during the solar proton event of July 14, 2000. J Geophys Res 108(A3):1103

Roldugin VC, Maltsev YP, Vasiljev AN, Schokotov AY, Belyajev GG (2004) Schumann resonance frequency increase during solar X-ray bursts. J Geophys Res 109:A01216. doi:10.1029/2003JA010019

AQ8 Sanfui M, Haldar DK, Biswas D (2015) Studies on different geophysical and extra-terrestrial events within the Earth–ionosphere Cavity in terms of ULF/ELF/VLF radio waves. Astrophys Space Sci (in final review)

Sátori G, Szendrői J, Verő J (1996) Monitoring Schumann resonances-I. Methodol J Atmos Terr Phys 58:1475–1481

Sátori G, Williams ER, Boldi R, Füllekrug M (2000) Systematic variations of Schumann resonances frequencies on the 11-year solar cycle at multiple stations. EOS Trans AGU 81(48):A12B-01

Sátori G, Williams E, Mushtak V (2005) Response of the Earth–ionosphere cavity resonator to the 11-year solar cycle in X-radiation. J Atmos Sol Terr Res 67:553–562

AQ9 Sátori G, Mushtak V, Williams E (2009) Schumann resonance signature of global lightning activity. In: Betz HD, Schumann U, Laroche P (eds) Lightning: principles, instruments and applications: review of modern lightning research. Springer, Berlin, pp 347–386

Schlegel K, Füllekrug M (1999) Schumann resonance parameter changes during high-energy particle precipitation. J Geophys Res 104:10111–10118

Schumann WO (1952) Über die strahlunglosen Eigenschwingungen einer leitenden Kugel, die von einer Luftschicht und einer Ionosphärenhülle umgeben ist. Z Naturforsch A 7:6627–6628

Sentman DD (1990) Approximate Schumann resonance parameters for a two-scale-height ionosphere. J Atmos Terr Phys 52:35–46

Sentman, DD, Heavner MJ, Baker DN, Cayton TE, Fraser BJ (1996) Effects of solar storms on the Schumann resonances in late 1989. In: 10th Annual conference on atmospheric electricity, society of atmospheric electricity of Japan

Sentman DD, Fraser BJ (1991) Simultaneous observations of Schumann resonances in California and Australia: evidence for intensity modulation of the local height of the D-region. J Geophys Res 96:15973

Shvets AV, Nickolaenko AP, Belyaev GG, Schekotov AY (2005) Analysis of Schumann resonance parameter variations associated with solar proton events. Telecommun Radio Eng 64(9):771–791

Tanaka YT, Hayakawa M, Hobara Y, Nickolaenko AP, Yamashita K, Sato M, Takahashi Y, Terasawa T, Takahashi T (2011) Detection of transient ELF emission caused by the extremely intense cosmic gamma-ray flare of 27, December 2004. Geophys Res Lett 38:L08805. doi:10.1029/2011GL047008

Thomson NR, Rodger CJ, Dowden RL (2004) Ionosphere gives size of greatest solar flare. Geophys Res Lett 31:L06803. doi:10.1029/2003GL019345

Toledo-Redondo S, Parrot M, Salinas A (2012) Variation of the first cut-off frequency of the Earth–ionosphere waveguide observed by DEMETER. J Geophys Res 117:A04321. doi:10.1029/2011JA017400

Verő J, Szendrői J, Sátori G, Zieger B (2000) On spectral methods in Schumann resonance data processing. Acta Geod Geophys Hungary 35:105–132

Veronig AM, Temmer M, Hanslmeier A (2004) The solar soft X-ray background flux and its relation to flare occurrence. Sol Phys 219:125–133

Wait JR (1962) Electromagnetic waves in stratified media. Pergamon, New York

Whitten RC, Popoff IG (1971) Fundamentals of aeronomy. Wiley, New York

Williams ER, Mareev EA (2014) Recent progress on the global electrical circuit. Atmos Res 135–136:208–227

Williams ER, Sátori G (2007) Solar radiation-induced changes in ionospheric height and the Schumann resonance waveguide on different timescales. Radio Sci. doi:10.1029/2006RS003494

Williams E, Guha A, Boldi R, Sátori G, Koloskov A and Yampolski Y (2014) Global circuit response to the 11-year solar cycle: changes in source or in medium? XV. In: International conference on atmospheric electricity, Norman, Oklahoma

Journal : Small 10712 Dispatch : 5-3-2016 Pages : 33
Article No. : 9369 LE TYPESET
MS Code : GEOP-D-15-00044 CP DISK

Yang H, Pasko VP (2006) Three-dimensional finite difference time domain modeling of the diurnal and seasonal variations in Schumann resonance parameters. Radio Sci 41:RS2S14. doi:10.1029/2005RS003402

Zhou H, Qiao X (2015) Studies on the variations of the first Schumann resonance frequency during the solar X-ray burst on 7 March 2012. J Geophys Res (Atmospheres). doi:10.1002/2014JD022696