Journal of Lightning Research, Volume 1, 2007, pages 1 -15

Schumann Resonances in Lightning Research

Colin Price, Olga Pechony, Eran Greenberg

Department of Geophysics and Planetary Sciences, Tel Aviv University, Israel 69978.

Abstract

Schumann resonances (SR) are global electromagnetic resonances excited primarily by lightning discharges. This review is aimed at the reader generally unfamiliar with Schumann resonances. Our goal is to give some historical context to SR research, and to show the extensive use of Schumann resonances in a variety of lightning-related studies in recent years, ranging from estimates of the spatial and temporal variations in global lighting activity, connections to global climate change, transient luminous events and extraterrestrial lightning. We present both theoretical and experimental results of the global resonance phenomenon. It is our hope that this review will increase the interest in Schumann resonances among lightning researchers previously unfamiliar with Schumann resonance studies. Keywords: Schumann resonance, lightning, ELF, climate, transient luminous event, planetary lightning.

Index Terms

Schumann Resonance, ELF, global lightning

1 INTRODUCTION

Schumann resonances (SR) are global electromagnetic resonances excited primarily by lightning discharges in the cavity between the Earth surface and the ionosphere. SR are observed in the power spectra of the natural electromagnetic background noise, as separate peaks at extremely low frequencies (ELF) around 8, 14, 20, 26 and 32 Hz (Figure 1).

The first suggestion that an ionosphere existed, capable of trapping electromagnetic waves, was made by Heaviside and Kannelly in 1902. It took another twenty years before Appleton, in 1924, was able to prove experimentally the existence of the ionosphere. However, even prior to this the first documented observations of global electromagnetic resonances were made by Nikola Tesla and formed the basis for his scheme for wireless communication [1]. Although some of the most important mathematical tools for dealing with spherical waveguides were developed by Watson [2], it was Winfried Otto Schumann who first studied the theoretical aspects of the global resonances of the earth-ionosphere waveguide system, known today as the Schumann resonances. Schumann, together with Köning, attempted to measure the resonant frequencies [3-6]. However, it was not until measurements made by Balser and Wagner [7-11] that adequate analysis techniques were available to extract the resonance information from the background noise.

Since then there has been an increasing interest in SR in a wide variety of fields. From the very beginning of SR studies, they were used to track global lightning activity [9, 12-15]. As a result of the connection between lightning activity and the Earth's climate, it has been suggested that SR may be used to monitor global temperature variations [16] and variations of upper water vapor [17, 18]. It was suggested that extraterrestrial lightning may also be detected and studied using SR [19-21]. SR has been used for research and monitoring of the lower ionosphere on Earth and suggested for exploration of lower ionosphere parameters on celestial bodies [19, 22]. One of the most interesting applications of SR research is the tracking of large-scale ionospheric perturbations. SR can help track geomagnetic disturbances, such as solar proton events, solar flares and γ-ray bursts [23-32]. Nuclear explosions have also been known to leave their signature in SR records [11, 33, 34]. More recently, Schumann resonances are used for monitoring transient luminous events – sprites and elves [35-39]. A new field of interest using SR is related to short-term earthquake prediction [40-42]. Schumann resonances have gone beyond the boundaries of physics, invading medicine [43], while raising interest in artists and musicians, and conquering such exotic fields as psychobiology and yoga. In this review we will

Submitted: 19/02/2006

Journal of Lightning Research

Accepted: 20/09/2006

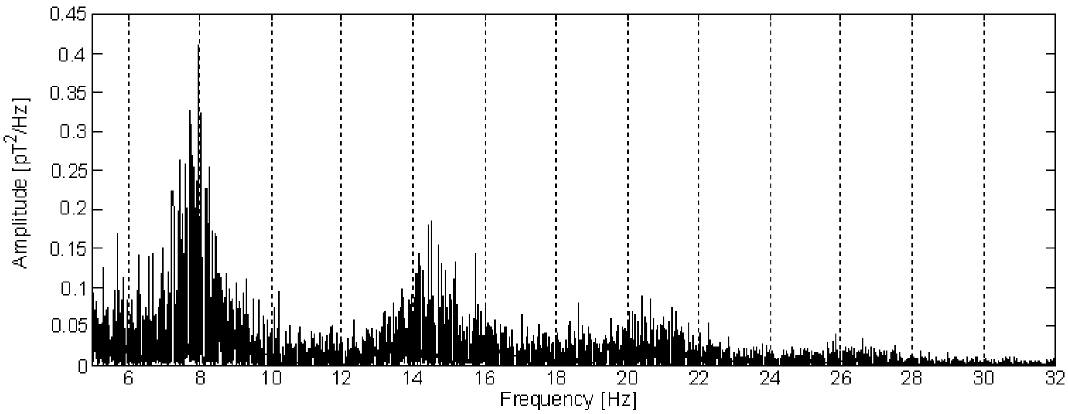

Figure 1: Schumann resonances in a sample spectrum of ELF natural electromagnetic signal (magnetic field north-south component) recorded at Mitzpe Ramon (32N, 34E) station, Israel

concentrate only on Schumann resonance studies associated with lightning research.

2 THEORETICAL BACKGROUND

Lightning discharges are considered as the primary natural source of SR. Lightning channels behave like a huge antenna which radiates electromagnetic energy as signals of impulsive nature at frequencies below about 100 kHz [44]. Lightning signals below 100 Hz are very weak, but the earth-ionosphere waveguide behaves like a resonator at ELF frequencies and amplifies the spectral signals from lightning at the resonance frequencies [44].

If the terrestrial waveguide was an ideal one, the resonant frequencies f_n would have been determined by the earth's radius a and the speed of light c – (1) [3]. However, the Earth-ionosphere waveguide is not a perfect electromagnetic cavity. Losses due to finite ionosphere conductivity make the system resonate at lower frequencies than would be expected in an ideal case, and the observed peaks are wide. In addition there are a number of horizontal asymmetries – day-night transition, latitudinal changes in the Earth magnetic field, sudden ionospheric disturbances, polar cap absorption, etc. that complicate the SR power spectra.

$$f_n = \left(c/2\pi a\right)\sqrt{n\left(n+1\right)} \quad (1)$$

The problem of wave propagation in the Earth-ionosphere cavity is most naturally formulated in spherical coordinates (r,θ,φ). The excitation source is represented by a vertical dipole with a current moment (Ids) located between two concentric spherical shells at θ=0. Radius of the inner shell – the Earth, is denoted by $r=a$, and the radius of the outer shell – the ionosphere – by $r=a+h$, assuming sharp and frequency independent upper boundary. Both the observer and the source are assumed to be located on the Earth surface. Maxwell equations are then solved assuming time dependence of $e^{i\omega t}$ and requiring continuity on the boundaries (ground-cavity transition at $r=a$, and cavity-ionosphere transition at $r=a+h$). The electric and magnetic components are then [44]:

$$E_r = i\frac{Ids}{8\pi a^2\varepsilon_0 f}\frac{\nu(\nu+1)}{h}\frac{P_\nu^0(-\cos\theta)}{\sin\nu\pi}$$
$$H_\varphi = -\frac{Ids}{4a}\frac{1}{h}\frac{P_\nu^1(-\cos\theta)}{\sin\nu\pi} \quad (2)$$

The resulting fields are shown in Figure 2 for the first three SR modes.

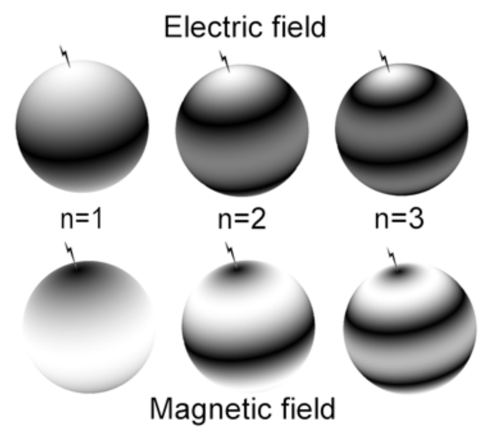

Figure 2: Electric and magnetic fields of the first three SR modes.

In (2) ε_0 is a free space permittivity and P_ν^l are the associated Legendre functions. Complex parameter ν is calculated in terms of complex sine of the wave incidence angle S via [45]:

$$S^2 = \nu\left(\nu+1\right)/\left(k_0 a\right)^2 \quad (3)$$

where κ_0 is the free space wave number. The dimensionless quality factor Q of the resonant cavity may be determined as a ratio between the stored energy and the energy loss per cycle. Considering only the electrically stored energy [45]:

$$Q = \frac{\operatorname{Re} S}{2 \operatorname{Im} S} \quad (4)$$

On Earth, the resonance is characterized by a quality factor Q ranging from 4 to 6 [46]

More realistic models are far more complex. Methods of introducing more complicated ionosphere structure include two-layer [48] and multi-layer models [49-52], and the more realistic two-exponential [53], “knee” [54], and “multi-knee” [21] profiles.

3 SR MEASUREMENTS

The electromagnetic sensors used to measure Schumann resonances consist of two horizontal antennas for receiving the magnetic field in the north-south direction (H_{NS}) and the east-west direction (H_{EW}) and one vertical antenna for observing the vertical electric field, E_Z (Figure 3). Since Schumann resonance frequencies are extremely low, practical antennas would have to be hundreds of kilometers long. In addition, the SR electric field is of the order of mV/m, which is much smaller then the static electric field in the atmosphere which ranges from 100V/m in the fair weather to kV/m on a stormy day. Furthermore, the SR magnetic field is in the pT range – orders of magnitude smaller then the Earth’s magnetic field. Therefore, special receivers and antennas are required to measure SR. The electric component is commonly measured with a ball antenna, suggested by [55], connected to a high-impedance amplifier. The magnetic field is measured with magnetic induction coils consisting of tens of thousands of turns around material with very high magnetic permeability.

The sampling frequency can vary from several tens of Hz to a few hundreds of Hz in order to cover the SR band without aliasing. It is advisable to save all raw data for later post-processing, although some groups use real-time analysis and save only the spectral parameters of the SR (peak frequency, peak amplitude, and Q-factor) [56], together with short time segments of ELF transients. In the time domain, the electric and magnetic signals consist of a background signal, which is a superposition of individual pulses arriving from about 50 random lightning flashes per second occurring all over the world. Superimposed upon the background noise are intense transients from individual powerful lightning discharges, with amplitudes often ten times higher than that of the background noise [57]. After processing the time series' by using the Fast Fourier Transform (FFT) algorithm, SR modes can usually be observed in the frequency domain at 8, 14, 20, 26… Hz.

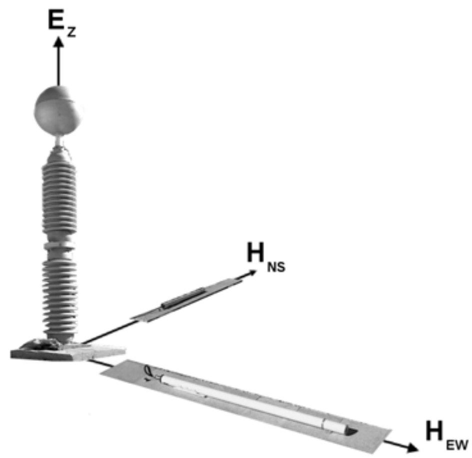

Figure 3: Schematic setup of SR receiving station: vertical antenna receives the electric field and the two buried horizontal antennas receive the north-south and east-west magnetic field components.

Man-made noise produces various interferences in the ELF ranging from radiation from power supply lines to traffic and pedestrians [46], forcing to locate SR measuring stations in isolated rural areas, away from industrial activity. At the site the electromagnetic field sensors should be located away from power supply lines. Complete battery supply is preferable, but is expensive and limits long-term monitoring. Open spaces with uniform underlying geology and well conducting soil should be chosen for the site [46]. The field sensors are exposed to external static fields – fair weather field of ~100 V/m and the geomagnetic field of ~0.5 Gauss, and therefore the slightest vibration of an antenna will result in a huge signals induced at the input of the receiver. Hence the horizontal magnetic antennas are buried in the ground to avoid the signals induced by ground vibrations or wind. Ideally, electric and magnetic channels should be identical, be calibrated periodically, sampled using a 16 bit A/D (analog-to-digital) converter, a notch filter for the industrial 50 Hz interference, and be equipped by a GPS clock for time stamps.

The duration of data collection of up to 10 minutes is needed to obtain stable estimates of the SR spectrum. Nickolaenko and Hayakawa [46] suggest that this may explain the unsuccessful early experiments by Schumann and König [6] focused on the detection of the global resonances: the natural signal is actually random "noise", and the resonance peaks become visible only after relatively long integration time. A 10 minutes interval was used in the first successful experiment by Balser and Wagner [7].

4 SR BACKGROUND OBSERVATIONS OF GLOBAL LIGHTNING ACTIVITY

At any given time there are about 2000 thunderstorms around the globe [13, 15, 16, 55, 58, 59]. Producing ~50 lightning events per second [60], these thunderstorms create the background SR signal.

Determining the spatial lightning distribution from the background SR records is a complex problem: in order to properly estimate the lightning intensity from SR records it is necessary to account for distance to sources. The common approach to this problem is based on the preliminary assumption on the spatial lightning distribution. The most widely used are the models of the three thunderstorm centers – continental and island Southeast Asia, Africa and South America [15, 61-65], and a single thunderstorm center traveling around the globe [46, 66, 67]. An alternative approach is placing the receiver at the North or South Pole, which remain approximately equidistant from the main thunderstorm centers during the day [68]. A distinct method, not requiring preliminary assumptions on the lightning distribution [69] is based on the decomposition of the average background SR spectra, utilizing ratios between the average electric and magnetic spectra and between their linear combinations.

The best documented and the most debated features of the Schumann resonance phenomenon are the diurnal variations of the background SR power spectrum. Some of the earliest studies were made by [9, 12, 70, 71]. The first investigators realized that SR field power variations were related to global thunderstorm activity [9, 12, 70, 72]. Thus SR measurements became a convenient tool for studying global lightning activity [16, 56, 61, 73-77].

Figure 4 shows the 4-year (1999-2002) mean diurnal and seasonal power variations of the first SR mode from the Mitzpe-Ramon, Israel ELF station. Geographical location of the MR site (32N, 34E) results in the domination of African lightning sources in the east-west oriented horizontal magnetic detector (H_{EW}) and the north-south oriented horizontal magnetic detector (H_{NS}) is dominated by sources from Asia and America. The vertical electric detector (E_Z) is equally sensitive in all directions and therefore measures global lightning [56]. Two maxima in the H_{NS} component are easily identified around 9:00 and 20:00 UT and are associated with increased thunderstorm activity from south-east Asia and South America at the late afternoon, local time. In the H_{EW} component there is a strong maximum around 14:00 UT associated with the peak in African lightning activity. The three dominant maxima are clearly seen during all seasons, associated with the three "hot spots" of planetary lightning activity. The time and amplitude of the peaks vary throughout the year, reflecting the seasonal changes in lightning activity.

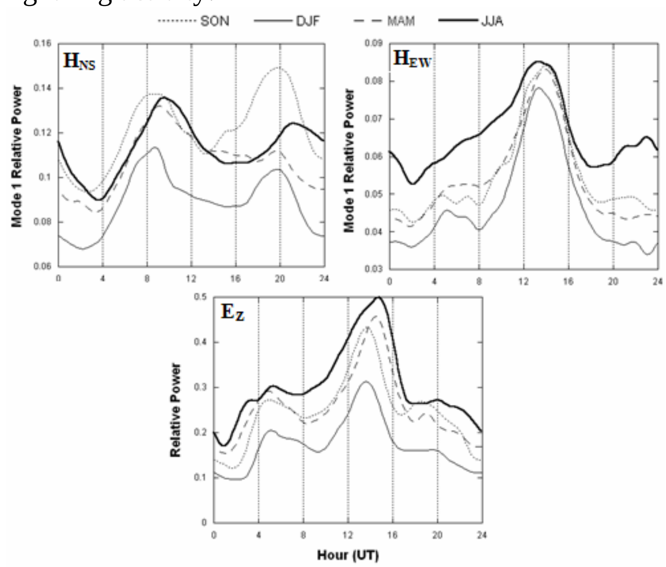

Figure 4: The 4-year mean diurnal and seasonal variations of the SR power for the first mode – individual electromagnetic components of the SR field. From [56].

In the early literature the observed diurnal variations were explained by the variations in the source-receiver geometry [9] and it was concluded that no particular systematic variations of the ionosphere are needed to explain these variations [73]. Subsequent theoretical studies supported the early estimations of the negligible influence of the ionosphere day-night asymmetry (difference between day-side and night-side ionosphere conductivity) on the observed variations in SR field intensities [46, 66, 78-80]. The interest in the influence of the day-night asymmetry of the ionosphere conductivity on SR field power arose with a new strength in the 1990s, after publication of a work by [59]. A technique was developed in [59] to separate the global and the local contributions to the observed field power variations using records obtained simultaneously at two stations. The local contribution was interpreted by [59] as ionosphere height variation. Their work convinced many scientists in the importance of the ionospheric day-night asymmetry and inspired numerous experimental studies. However recently it was shown that results obtained by [59] can be simulated with a uniform model (without taking into account ionosphere day-night variation) and therefore cannot be interpreted in terms of ionosphere height variation [81].

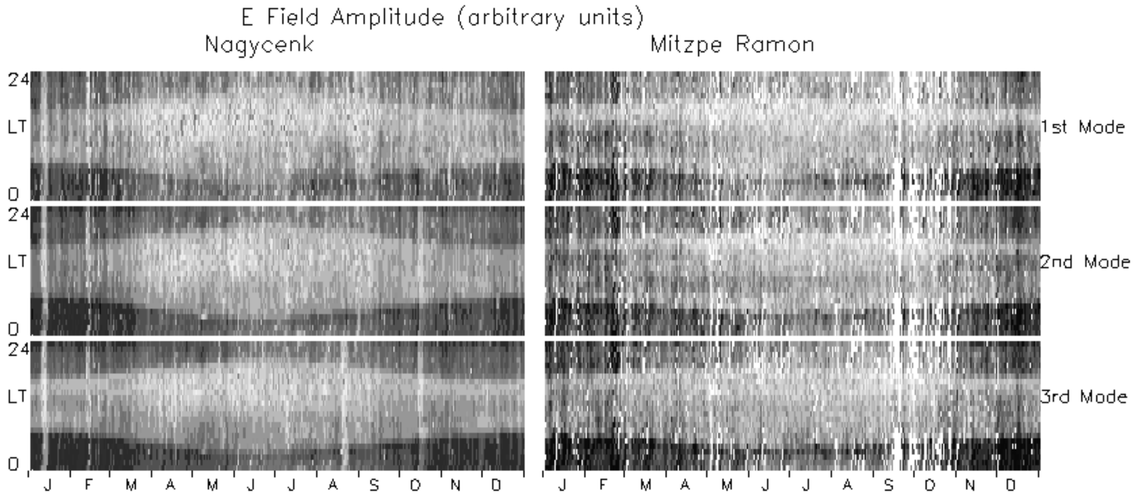

Figure 5: The 4-year mean diurnal and seasonal variations in the SR amplitude (E_z) at Mitzpe Ramon, Israel, for 8Hz, 14Hz, and 20Hz (right panels). Similar plots are presented from Nagycenk Hungary for 8 years (left panels). [from 56].

Figure 5 shows diurnal and seasonal amplitude variations in the electric field of the first three SR modes for Nagycenk, Hungary station (1994-2001) – the left panels, and for Mitzpe-Ramon station (1999-2002 average) – the right panels. The data recorded at both stations demonstrates significant diurnal and seasonal variations of SR fields. When plotted in this way, a characteristic lens-shape pattern is revealed. This lens-shape strongly resembles the shape of the terminator (the day-night transition) and hence is termed the "terminator effect". Such similarity seems to support the suggestion of a significant influence of the day-night ionosphere asymmetry on SR [59, 83]. However, such variations may be as well explained by the migration of thunderstorms [46, 82].

If SR records are to be used to monitor variations in the global thunderstorm activity by tracking changes in SR field intensities, successful monitoring of global thunderstorm activity relies on the proper interpretation of experimental data. It is vital to understand and correctly interpret the major features of SR field power variations. For this theoretical modeling is needed.

5 SR TRANSIENT MEASUREMENTS OF GLOBAL LIGHTNING ACTIVITY

One of the most interesting problems in SR studies is determining the lightning source characteristics (the "inverse problem"). Temporally resolving each individual flash in the background SR signal is impossible. However there are intense ELF transient events, also named ''Q bursts'', which appear as prominent excursions above the SR background signal (Figure 6). Q-bursts are triggered by intense lightning strikes, associated with a large charge transfer and often high peak current [35, 55]. Amplitudes of Q-bursts can exceed the SR background level by a factor of 10 and they appear with intervals from ~10sec to a few minutes [69]. This allows us to consider the Q-bursts as isolated events and to determine the source lightning locations [66, 84-90].

The lightning location problem can be solved with either multi-station or single-station techniques. The multi-station techniques are the more accurate, but require more complicated and expensive facilities, involving a network of direction finders or time-of-arrival meters [91]. Single-station systems usually combine a direction finder with a source-receiver distance estimation technique. The transients can be geolocated with source-observer distance (SOD) or source-bearing techniques, based on the relationship between the electric and the magnetic field components [35, 37, 84, 87, 89, 92, 93]. Geolocation of source lightning can be identified with an accuracy of ~1 Mm from single-station measurements.

Source location techniques can be confirmed using general location of flashes above continental regions [84, 88], the proximity of cold cloud tops in visible and infra-red (IR) satellite images [94], global lightning measurements from space by the Optical Transient Detector (OTD) and the Lightning Imaging Sensor

(LIS) [93], and local measurements of lightning with ground networks, such as US National Lightning Detection Network in North America [11].

6 SR IN TRANSIENT LUMINOUS EVENTS RESEARCH

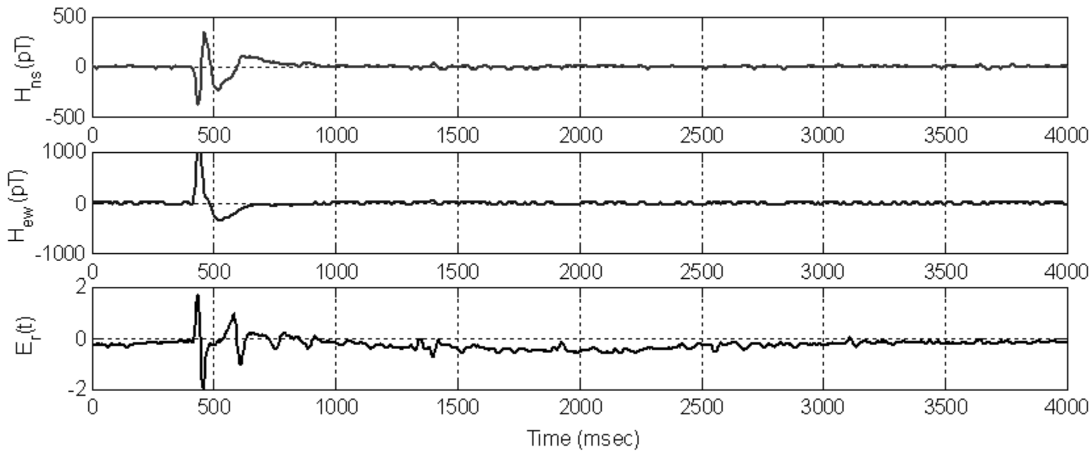

Figure 6: Example of ELF transient recorded at Mitzpe Ramon (32N, 34E) station, Israel.

It is now believed that many of the SR transients are related to newly discovered transient luminous events (TLEs), spectacular optical flashes in the upper atmosphere above active thunderstorms. The existence of TLEs was theoretically predicted by [95], and many pilots have reported about this phenomenon. But the official discovery came with the first image captured above a thundercloud by [96]. In the last 15 years there has been an extensive hunt for TLEs using photography from ground stations, aircrafts and space shuttles, leading to TLE documentation in different geographical locations all over the world [97-108].

TLEs can be classified into two main classes: sprites and elves [109], although there are also blue jets, halos and trolls. Both elves and sprites are short-lived luminous events associated with mesoscale convective systems. ELVE is an acronym for “Emissions of Light and Very low frequency perturbations from Electromagnetic pulse sources”. They are dim donut-shaped glow of ~200km radius, lasting typically ~1ms occurring at altitudes of ~90-100 km. SPRITES stands for “Stratospheric/mesospheric Perturbations Resulting from Intense Thunderstorm Electrification”. Sprites are reddish-orange due to collisions of accelerated electrons with nitrogen molecules [110]. They usually occur in clutters and have forms from jelly fish to carrots, to columns. Sprites stretch from the altitude range of 40–90km with horizontal extent of tens of km and typical lifetimes of tens of ms.

The physical mechanisms responsible for sprites and elves initiation are independent of the polarity of the lightning flash [110-115]; however the vast majority of sprites and elves are initiated by positive cloud-to-ground (CG) flashes [36, 116]. These powerful positive flashes emit strong electromagnetic energy in the ELF range, indicative of continuing currents lasting over time scales of at least a few ms [116], and thus can be detected in the SR band. [36] suggested that sprites, the most common TLE, are produced by positive CG occurring in the stratiform region of a thunderstorm system, and are accompanied by large-amplitude transient pulses ("Q-burst") in the SR band. Recent observations [35-38, 90, 117] reveal that occurrences of sprites and transient SR are highly correlated.

SR records can be used to estimate the magnitude of the charge removed from cloud bottom to ground [118, 119], which appears to be one of the crucial parameters in determining which lightning discharge can produce sprites. A method of charge moment estimation of sprite-inducing CG discharges from SR data was developed by [35], who showed that the charge moments of sprite inducing CG discharges range from 200 to 2000Ckm. [120] suggested a sprite initiation probability as a function of charge moments of positive CG discharges, and hence the charge moment estimation derived from SR data can possibly enable us to estimate the global occurrence rate of sprites.

Recently, it was suggested that sprites can chemically change the concentration of NO_x and HO_x in the mesosphere and lower thermosphere [121]. These chemical products may lead to an impact on the global cooling or heating in the middle atmosphere, therefore it is particularly important to determine global occurrence locations and rates of sprites. Since sprites are a rather rare, occurring at rate of only a few per minute (while regular lightning occurs at a rate of 50-100 flashes per second around the globe) SR appears to be one of the most convenient and low-cost tools for continuous TLE monitoring.

7 USING SR AS A CLIMATE RESEARCH TOOL

The warming of the Earth has been the subject of intense debate and concern for many scientists for at least the past decade. One of the important aspects in understanding global climate change is the development of tools and techniques that would allow continuous and long-term monitoring of processes affecting the global climate. Schumann resonances are one of the very few tools that can provide such global information reliably and cheaply.

It was suggested by [16] that global temperature may be monitored via the SR. The link between Schumann resonance and temperature is lightning flash rate, which increases nonlinearly with temperature [16, 122]. The nonlinearity of the lightning-to-temperature relation provides a natural amplifier of the subtle (several tenths of 1°C [123, 124]) temperature changes and makes Schumann resonance a sensitive "thermometer". Moreover, the ice particles that are believed to participate in the electrification processes which result in a lightning discharge [125] have an important role in the radiative feedback effects that influence the atmosphere temperature. Schumann resonances may therefore help us to understand these feedback effects.

[16] compared a 5.5-year monthly mean time series of the first mode SR magnetic field data recorded at Kingston, Rhode Island (71W, 41N) with the monthly mean fluctuations in surface (dry-bulb) temperature for the entire tropics. It was shown that SR amplitude quite closely follows the temperature variations. Warmer periods were found to be associated with enhanced magnetic field amplitude, i.e. increase in global lightning activity, and colder periods – with suppressed amplitude, i.e. global decrease in lightning activity. Additional analysis using other SR data sets also show strong positive correlations between surface temperatures and SR power on seasonal and daily timescales [18]. Figure 7 presents an example of daily observations of 10Hz magnetic field recorded at Arrival Heights, Antarctica and MSU satellite temperature, showing clear correlation between the two parameters.

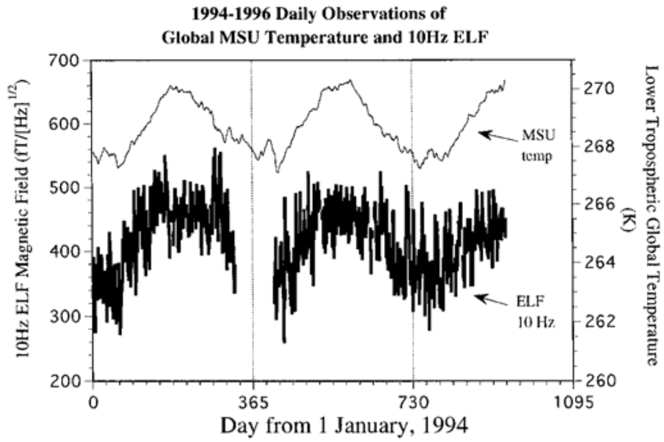

Figure 7: 10Hz magnetic field records (Arrival Heights, Antarctica) and MSU satellite temperature data.

Monitoring and predicting global climate change requires major advances in understanding and modeling of factors that determine atmospheric concentrations of greenhouse gases and the feedbacks that determine the sensitivity of the climate system to a given increase in those gases. Continental deep-convective thunderstorms produce most of the lightning discharges on Earth. In addition, they transport large amount of water vapor into the upper troposphere, dominating the variations of global UTWV. Tropospheric water vapor is a key element of the Earth's climate, which has direct effects as a greenhouse gas, as well as indirect effect through interaction with clouds, aerosols and tropospheric chemistry. Upper tropospheric water vapor (UTWV) has a much greater impact on the greenhouse effect than water vapor in the lower atmosphere [126], but whether this impact is a positive, or a negative feedback is steel uncertain [127-131]. The main challenge in addressing this question is the difficulty in monitoring UTWV globally over long timescales. [17, 18] suggest that changes in the UTWV can be derived from records of SR. Figure 8 shows an example of the connection between daily SR amplitudes and upper tropospheric water vapor.

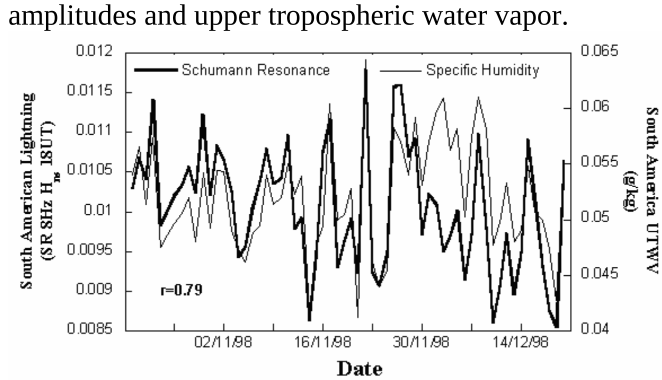

Figure 8: Daily SR 8Hz magnetic field records and upper tropospheric water vapor.

The above results show that two of the most important parameters of global climate change – surface temperature and UTWV, can be monitored with SR, utilizing its relation to worldwide thunderstorm activity. One of the great advantages of this method is availability of long-term calibrated data which can provide past and future records of global climate variations on Earth.

8 SR IN EXTRATERRESTRIAL LIGHTNING RESEARCH

Existence of Schumann resonances depends generally on two factors – presence of a substantial ionosphere with electric conductivity increasing with height from low values near the surface (or a high-conductivity layer, in case of gaseous planets) to form an ELF waveguide, and a source of excitation of electromagnetic waves in the ELF range. In Solar System there are number of candidates for SR detection: Venus, Mars, Jupiter, Saturn and its moon Titan.

The speculations that lightning occurs on Venus first arose about 30 years ago. The strongest evidence for lightning on Venus comes from the impulsive electromagnetic waves seen by the Venera 11 and 12 landers [132-135] and the Pioneer Venus Orbiter [136, 137]. On Mars lightning activity has not been detected, but charge separation and lightning strokes are considered possible in the Martian dust storms [138-141]. Jupiter is the only planet where lightning activity is well established. Existence of lightning on this planet was predicted by [142] and it is supported by data from Galileo, Voyagers 1 and 2, Pioneers 10 and 11 and Cassini [143, 144]. Although Saturn is similar enough to Jupiter to expect intensive lightning activity, the three visiting spacecrafts – Pioneer 11 in 1979, Voyager 1 in 1980 and Voyager 2 in 1981, failed to provide convincing evidence of lightning activity [144]. Recently a strong storm was monitored on Saturn by Cassini spacecraft. The storm was a possible source of radio emissions, believed to come from lightning discharges. However no visible lightning flashes were recorded [145]. Although no lightning was observed during Voyager flybys of Titan in 1980 and 1981, it was long suggested that lightning dischargers do take place on this moon of Saturn [146, 147]. However recent data from Cassini/Huygens seems to indicate that there is no lightning activity on Titan.

Modeling of SR parameters on the planets and moons of the Solar System is complicated by the lack of knowledge of the waveguide parameters. SR frequencies depend on the structure of the lower part of the ionosphere, which is not sufficiently studied. On Jupiter and Saturn the situation is yet more complicated. Little is known about the electrical parameters of the interior of Jupiter and Saturn. Even the question of what should serve as the lower waveguide boundary is a non-trivial one in the case of these gaseous planets. To our best knowledge there are no works dedicated to SR on Saturn. Up to date there was only one attempt to model Schumann resonances on Jupiter – in the [22]. Calculations yielded resonant frequencies of approximately 0.76, 1.35 and 1.93 Hz with quality factors of roughly 7, predicting sharp, pronounced peaks.

The situation with other planets is a little better. SR on Venus were studied by [19, 21]. Both studies, basing on different conductivity profiles and with different models yielded very close resonant frequencies: around 9, 16 and 23 Hz. The quality factors, though, differ substantially: [19] obtained Q-factors of ~5 while [21] acquired Q~10. Such a difference – by a factor of two, was predicted by [19] for more sophisticated ionosphere representations.

Martian global resonances were modeled by [21, 148, 149]. The results of the three studies are somewhat different. [148] obtained the resonant frequencies at about 13, 25 and 37 Hz with Q-factors around 3.5. The frequencies calculated by [21] are lower: 8.6, 16.3 and 24.4 Hz, with Q-factors of ~2.4. The disparity can probably be explained by the different models of Martian lower ionosphere used in the two studies. Nevertheless the low quality factors obtained in both studies show that pronounced sharp peaks at resonance frequencies should not be expected for the Marian ELF waveguide. Significantly different results were obtained by [149], where several ionosphere models were used. The firs resonance occurred at 11-12 Hz (depending on ionosphere model), the second and third resonances interfered to form a single peak at 21-25 Hz and the forth, fifth and sixth modes produced a very smooth-shaped peak at around 60 Hz.

The ionosphere of Titan is perhaps the most thoroughly modeled today. The recent interest in the largest satellite of Saturn is associated with the Cassini/Huygens Mission and expectations of finding evidence of lightning activity on Titan. Consequently, SR on Titan received more attention then resonances on other celestial bodies. The resonant frequencies obtained for various ionospheric conductivity profiles tested in studies by [150-152] range (for realistic models) from 11.0 to 15.0Hz for the first mode, 21.2–

27.8 Hz for the second and 35.6–41.6 for the third. Unfortunately, the quality factors were not calculated in these studies. Comparable results were obtained by other authors: resonant frequencies of 19.9, 35.8 and 51.8 Hz with Q-factors of 1-3 were obtained by [153], and 11.8, 22.5 and 34.1 Hz with Q-factors of ~2 – by [21]. The low Q-factors acquired in these two studies show that the expected peaks, should lighting activity be found on Titan, are rather wide.

Schematic representation of Schumann resonances on Venus, Earth, Mars, Titan and Jupiter is shown on Figure 9. Today there is no possibility to validate SR parameters calculated for other planets and moons. The values of the resonance frequencies and quality-factors are very dependant on the ionospheric profile models. The accuracy of the latter is limited, and a deeper knowledge of planetary ionospheres would allow more precise predictions of Schumann resonance parameters. On the other hand, experimental evaluation of SR parameters can aid in the elaboration of the effective model of the ionospheric conductivity profile, and contribute substantially to the knowledge of lower ionospheres on planets of the Solar system.

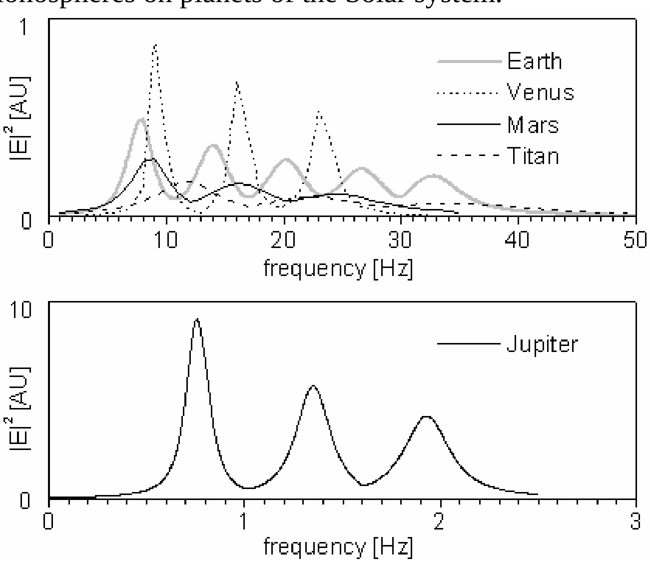

Figure 9: Schematic representation of Schumann resonances on Venus, Earth, Mars, Titan and Jupiter.

9 SUMMARY

Being a global phenomenon, Schumann resonances have numerous applications in lightning research. Background SR records can serve as a convenient and a low-cost tool for global lightning activity monitoring. Q-bursts – large-amplitude excursions above the background level can be used to geolocate intense lightning strikes. These large-amplitude pulses are related to the occurrence of sprites and elves, which therefore can be tracked using SR records. Schumann resonances are one of the few tools which, through variations in global lightning activity, can provide continuous and long-term monitoring of such important global climate change parameters as surface temperature and upper tropospheric water vapor. An additional application of SR is extraterrestrial lightning research. Schumann resonances can be used to detect and, if necessary, monitor lightning activity on the planets and moons of the solar system.

There are still many open questions in SR research: importance of the day-night variation in the ionosphere conductivity profile, latitudinal changes in the Earth magnetic field, sudden ionospheric disturbances, polar cap absorption, accuracy of source geolocation, and determination of the spatial lightning distribution from the background records. Despite these open problems SR is one of the most promising tools in a variety of fields related to lightning research.

10 REFERENCES

1. Tesla N. (1905), The Transmission of Electrical Energy Without Wires As A Means Of Furthering World Peace, Electrical World And Engineer, January 7: 21–24.
2. Watson, G.N. (1918), The diffraction of electric waves by the earth, Proc. Roy. Soc. (London) Ser.A 95(1918), 83-99.
3. Schumann W. O. (1952), Über die strahlungslosen Eigenschwingungen einer leitenden Kugel, die von einer Luftschicht und einer Ionosphärenhülle umgeben ist, Zeitschrift und Naturfirschung, 7a, 149-154.
4. Schumann W. O. (1952), Über die Dämpfung der elektromagnetischen Eigenschwingnugen des Systems Erde – Luft – Ionosphäre, Zeitschrift und Naturfirschung, 7a, 250-252.
5. Schumann W. O. (1952), Über die Ausbreitung sehr Langer elektriseher Wellen um die Signale des Blitzes, Nuovo Cimento, 9, 1116-1138.
6. Schumann W. O. and H. König (1954), Über die Beobactung von Atmospherics bei geringsten Frequenzen, Naturwiss, 41, 183-184.
7. Balser M. and C. Wagner (1960), Measurement of the spectrum of radio noise from 50 to 100 c/s, J.Res. NBS, 64D, 415-418.
8. Balser M. and C. Wagner (1960), Observations of earth-ionosphere cavity resonances, Nature, 188, 638-641.

9. Balser M. and C. Wagner (1962), Diurnal power variations of the earth-ionosphere cavity modes and their relationship to worldwide thunderstorm activity, J.G.R., 67, 619-625.
10. Balser M. and C. Wagner (1962), On frequency variations of the earth-ionosphere cavity modes, J. G. R., 67, 4081-4083.
11. Balser M. and C. Wagner (1963), Effect of a high-altitude nuclear detonation on the earth-ionosphere cavity, J.G.R., 68, 4115-4118.
12. Holzer, R.E. (1958), World thunderstorm activity and extremely low frequency sferics, in Recent advances in atmospheric electricity, L.G. Smith, ed. 599-602, Pergamon Press.
13. Nickolaenko A. P. and L. M. Rabinowicz (1995) Study of the annual changes of global lightning distribution and frequency variations of the first Schumann resonance mode, J. A. S. T. P., 57(11), 1345-1348.
14. Nickolaenko A. P., L. M. Rabinowicz, M. Hayakawa (1998), Analyses of the ULF/ELF records performed in a seismo-active region, J. of Atmospheric Electricity, 18(1), 1-10.
15. Heckman S. J., E. Williams, B. Boldi (1998), Total global lightning inferred from Schumann resonance measurements, J. G. R., 103(D24), 31775-31779.
16. Williams, E.R. (1992), The Schumann resonance: a global tropical thermometer, Science, 256, 1184-1186.
17. Price, C. (2000), Evidence for a link between global lightning activity and upper tropospheric water vapor, Letters to Nature, 406, 290-293.
18. Price, C., M. Asfur (2006), Can lightning observations be used as an indicator of upper-tropospheric water-vapor variability, Bulletin of the Amer. Met. Soc., doi:10.1175/BAMS-87-3-xxx, in press.
19. Nickolaenko A. P., L. M. Rabinowicz (1982), On the possibility of existence of global electromagnetic resonances on the planets of Solar system, Space Res., 20, 82-89.
20. Nickolaenko A. P., L. M. Rabinowicz (1987), On the applicability of extremely low frequency global resonances in the studies of lightning activity at Venus, Space Res., 25, 301-308.
21. Pechony, O., C. Price (2004), Schumann resonance parameters calculated with a partially uniform knee model on Earth, Venus, Mars, and Titan, Radio Sci., 39(5), RS5007, doi:10.1029/2004RS003056.
22. Sentman D. D. (1990), Electrical conductivity of Jupiter's Shallow interior and the formation of a resonant planetary-ionosphere cavity, ICARUS, 88, 73-86.
23. Sao, K., M. Yamashita, S. Tanahashi, H. Jindon, K. Ohta (1973), Experimental investigations of Schumann resonance frequencies, J. Atmos. Terr. Phys., 35, 247– 253.
24. Cannon, P. S., and M. J. Rycroft (1982), Schumann resonance frequency variations during sudden ionospheric disturbances, J. Atmos. Terr. Phys., 44, 201–206.
25. Satori, G. (1993), Schumann-resonances and geomagnetic activity, IAGA Bull. 55, 206 pp., Int. Union Geod. Geophys., Buenos Aires, Brazil.
26. Sentman, D., M. J. Heavner, D. N. Baker, T. E. Cayton, B. J. Fraser (1996), ECects of solar storms on the Schumann resonances in late 1989, Proceedings of the 10th International Conference on Atmospheric Electricity, ICAE, Osaka, Japan, pp. 696–699.
27. Schlegel, K. and M. Fullekrug (1999), Schumann resonance parameter changes during high-energy particle precipitation, J. G. R., 104(10), 111–10,118.
28. Roldugin, V. C., Y. P. Maltsev, A. N. Vasiljev, E. V. Vashenyuk (1999), Changes of the first Schumann resonance frequency during relativistic solar proton precipitation in the 6 November 1997 event, Ann. Geophys., 17, 1293– 1297.
29. Roldugin, V. C., Y. P. Maltsev, G. A. Petrova, A. N. Vasiljev (2001), Decrease of the first Schumann resonance frequency during solar proton events, J. G. R., 106(18), 555–562.
30. Roldugin, V. C., Y. P. Maltsev, A. N. Vasiljev, A. V. Shvets, A. P. Nikolaenko (2003), Changes of Schumann resonance parameters during the solar proton event of 14 July 2000, J. G. R., 108(A3), doi:10.1029/2002JA009495.
31. Price, C., Mushtak V. (2001), The impact of the August 27, 1998, γ -ray burst on the Schumann resonances, J. A. S. T. P., 63, 1043-1047.
32. Satori, G., E. Williams, V. Mushtak (2005), Response of the Earth–ionosphere cavity resonator to the 11-year solar cycle in X-radiation, J. A. S. T. P., 67, 553-562.
33. Gendrin, R., and R. Stefant (1962), Effet de l'explosion thermonucleaire a tres haute altitude du 9 juillet 1962 sur la resonance de la cavite Terre-ionosphere: Resultats experimentaux, C.R. Acad. Sci. Paris, 255, 2273-2275.

34. Gendrin, R., and R. Stefant (1962), Effet de l'explosion thermonucleaire a tres haute altitude du 9 juillet 1962 sur la resonance de la cavite Terre-ionosphere: Interpretation, C.R. Acad. Sci. Paris, 255, 2493-2495.
35. Huang, E., E. Williams, R. Boldi, S. Heckman, W. Lyons, M. Taylor, T. Nelson, C. Wong (1999), Criteria for sprites and elves based on Schumann resonance observations, JGR-Atmospheres, 104(D14), 16943.
36. Boccippio, D. J., E. R. Williams, S. J. Heckman, W. A. Lyons, I. T. Baker, R. Boldi (1995), Sprites, ELF transients, and positive ground strokes, Science, 269, 1088–1091.
37. Price, C., M. Asfur, W. Lyons, T. Nelson (2002), An improved ELF/VLF method for globally geolocating sprite-produced lightning, G.R.L., 29(3), doi: 10.1029/2001GL013519.
38. Sato, M. and H. Fukunishi (2003), Global sprite occurrence locations and rates derived from triangulation of transient Schumann resonance events, G. R. L., 30(16), 1859, doi:10.1029/2003GL017291.
39. Sato, M., H. Fukunishi, M. Kikuchi, H. Yamagishi, W. A. Lyons (2003), Validation of sprite-inducing cloud-to-ground lightning based on ELF observations at Syowa station in Antarctica, J. A. S. T. P., 65, 607– 614.
40. Hayakawa, M. and Y. Fujinawa (1994), Electromagnetic Phenomena Related to earthquake Prediction, Terra Sci. Publ. Comp. Tokyo, 677.
41. Hayakawa, M. (1999), Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes, Terra Sci., Publ. Comp., Tokyo, 995.
42. Ohta, K., K. Ummeda, N. Watnabe, M. Hayakawa (2001), ULF/ELF emissions observed in Japan, possibly associated with the Chi-Chi earthquakes in Taiwan, Natural Hazards and Earth System Sciences, 1, 37–42.
43. Cherry, N. J. (2003), Human intelligence: The brain, an electromagnetic system synchronised by the Schumann Resonance signal, Medical Hypotheses, 60, 843-844.
44. Volland, H. (1984), Atmospheric Electrodynamics, Berlin: Springer-Verlag, 205p.
45. Wait, J.R. (1962), Electromagnetic waves in stratified media, Pergamon Press.
46. Galejs J. (1972), Terrestrial propagation of long electromagnetic waves, Pergamon Press.
47. Nickolaenko A. P. and M. Hayakawa (2002), Resonances in the Earth-ionosphere cavity, Kluwer Academic Publishers, Dordrecht-Boston-London.
48. Jones D. Ll. (1964), The calculations of the Q-factors and frequencies of Earth-ionosphere cavity resonances for a two-layer ionosphere model, J.G.R., 69, 4037-14041.
49. Jones D.Ll (1967), Schumann resonances and ELF propagation for inhomogeneous, isotropic ionosphere profiles, J. Atm. Terr. Phys., 29, 1037-1044.
50. Yamashita, M. (1967), Propagation of ELF radio waves to great distances below the unisotropic ionosphere, J. Atmos. Terr. Phys., 29, 937-948.
51. Yamashita, M. (1968), The propagation characteristics of ELF radio waves to great distances below the horizontally stratified ionosphere, J. Atmos. Terr. Phys., 30, 1943-1953.
52. Hynninen, E.M., Yu.P. Galyuck 1972: "The field of a vertical electric dipole over the spherical Earth's surface below the vertically inhomogeneous ionosphere", (in Russian),The Problems of Diffraction and Wave Propagation, 11, 109-115.
53. Greifinger, C., Ph. Greifinger (1978), Approximate method for determining ELF eigenvalues in the Earth-ionosphere waveguide, Radio Science, 13, 831-837.
54. Mushtak V.C., E.R. Williams (2002), ELF propagation parameters for uniform models of the Earth-ionosphere waveguide, J.A.S.T.P., 64, 1989-2001.
55. Ogawa, T., Y. Tanka, T. Miura, and M. Yasuhara (1966), Observations of natural ELF electromagnetic noises by using the ball antennas, J. Geomagn. Geoelectr., 18, 443– 454.
56. Price, C., A. Melnikov (2004), Diurnal, seasonal and inter-annual variations of the Schumann resonance parameters, J. A. S. T. P., 66(13-14), 1179.
57. Greenberg, E., C. Price, (2006), Diurnal variations of ELF transients and background noise in the Schumann resonance band, Radio Science, in press.
58. Clayton, M., and C. Polk (1977), Diurnal validation and absolute intensity of worldwide lightning activity, in Electrical Processes in Atmospheres, edited by H. Dolezalek and R. Reiter, pp. 440 – 449, Steinkopff, Darmstadt, Germany.
59. Sentman D. D., B. J. Fraser (1991), Simultaneous observation of Schumann resonances in California and Australia: evidence for intensity modulation by local height of the D region, JGR, 96(9), 15973-15984.

60. Christian H. J., R.J. Blakeslee, D.J. Boccippio, W.L. Boeck, D.E. Buechler, K.T. Driscoll, S.J. Goodman, J.M. Hall, W.J. Koshak, D.M. Mach, M.F. Stewart (2003), Global frequency and distribution of lightning as observed from space by the Optical Transient Detector, J.G.R., 108(D1), 4005.
61. Nickolaenko, A. P., Hayakawa, M., Hobara, Y., (1996), Temporal variations of the global lightning activity deduced from the Schumann resonance data, Journal of Atmospheric and Terrestrial Physics, 58, 1699-1709.
62. Nickolaenko A. P., G. Satori, B. Zieger, L. M. Rabinowicz, L. G. Kudintseva (1998), Parameters of global thunderstorm activity deduced from the long-term Schumann resonance records, J. A. S. T. P., 60(3), 387-399.
63. Satori, G., J. Szendroi, J. Vero, (1996), Monitoring Schumann resonances—I. Methodology. Journal Atmospheric and Terrestrial Physics 58, 1475–1481.
64. Belyaev, G.G., A. Yu. Schekotov, A.V. Shvets, A.P. Nickolaenko, (1999), Schumann resonances observed using Poynting vector spectra. J.A.S.T.P., 61, 751–763.
65. Shvets, A.V., (1999), Distance estimation to the world thunderstorm centers by measurement of the Schumann resonance background. XXVI General Assembly URSI, University of Toronto, Toronto, Ont., Canada, August 13–21, 1999, Abstracts, p. 297.
66. Bliokh, P. V., A. P. Nickolaenko, Yu. F. Filippov (1980), Schumann Resonances in the Earth-ionosphere cavity, D. Ll. Jones – ed., Peter Peregrinus, Oxford.
67. Yatsevich E. I., A. V. Shvets, L. M. Rabinowicz, A. P. Nickolaenko, G. G. Belyaev, A. Yu. Schekotov (2005), Results of comparing Schumann resonance observations with a model of the single world thunderstorm center, Izvestia Vuzov, Radiophysica, 48(4), 283-298. English translation is published in Radiophysics and Quantum Electronics.
68. Nickolaenko, A.P. (1997), Modern aspects of Schumann resonance studies, J.A.S.T.P., 59, 806–816.
69. Shvets A.V. (2001), A technique for reconstruction of global lightning distance profile from background Schumann resonance signal, J.A.S.T.P., 63, 1061-1074.
70. Raemer, H. R. (1961), On the extremely low frequency spectrum of the earth-ionosphere cavity response to electrical storms, J. G. R., 66, 1580-1583.
71. Polk, C. and F. Fitchen (1962), Schumann resonances of the earth-ionosphere cavity – extremely low frequency reception at Kingston, R.I., J.Res. NBS, 66D, 313-318.
72. Rycroft, M. J. (1963), Low frequency disturbances of natural origin of the electric and magnetic fields of the earth, Ph.D. thesis, University of Cambridge.
73. Madden T., W. Thompson (1965), Low-frequency electromagnetic oscillations of the Earth-ionosphere cavity, Rev. Geophys., 3(2), 211.
74. Polk, C. (1968), Relation of ELF noise and Schumann resonances to thunderstorm activity, in Planetary Electrodynamics, 2, 55-83, ed. H. Volland, CRC Press., Boca Ration, Florida.
75. Jones D. Ll. (1974), ELF-VLF radio wave propagation, J.A. Holtet, ed., Dordrecht: D. Reidel Publishing Company, 207.
76. Fullekrug, M., and A. C. Fraser-Smith (1997), Global lightning and climate variability inferred from ELF magnetic field variations, G. R. L., 24, 2411-2414.
77. Satori, G., and B. Zieger (1996), Spectral characteristics of Schumann resonances observed in Central Europe, J. G. R.-Atmospheres, 101, 29663-29669.
78. Large, D. B., J. R. Wait (1968), Theory of electromagnetic coupling phenomena in the earth-ionosphere cavity, J.G.R., 73(13), 4335.
79. Rabinowicz, L. M. (1988), Global electromagnetic resonances in non-uniform and anisotropic Earth-ionosphere cavity, Ph.D. thesis, Kharkov, 1988.
80. Nickolaenko, A. P. (1986), ELF radio wave scattering by the global non-uniformities of the Earth-ionosphere cavity, Izvestia Vuzov, Radiofizika, 29, 33-40. (in Russian).
81. Pechony, O., C. Price (2006), Schumann Resonances: interpretation of local diurnal intensity modulations, accepted to Radio Sci.
82. Pechony, O., C. Price, A.P. Nickolaenko (2006), Importance of the day-night asymmetry in Schumann resonance records, submitted to Radio Sci.
83. Melnikov A., C. Price, G. Satori, M. Fullekrug (2004), Influence of solar terminator passages on Schumann resonance parameters, J. A. S. T. P., 66(13-14), 1187.
84. Kemp, D.T., D. Ll. Jones (1971), A new technique for the analysis of transient ELF electromagnetic disturbances within

the Earth–ionosphere cavity, J. Atmos. Terr. Phys., 33, 567–572.

85. Ishaq, M., D.L. Jones (1977) Method of obtaining radiowave propagation parameters for the Earth–ionosphere duct at ELF, Electronic Letters, 13, 254–255.
86. Jones, D. Ll., C.P. Burke (1992), An experimental investigation of ELF attenuation rates in the Earth–ionosphere cavity, Journal of Atmospheric and Terrestrial Physics, 54, 243.
87. Nickolaenko A. P., I. G. Kudintseva (1994), A modified technique to locate the sources of ELF transients events, J.A.T.P., 56, 1493.
88. Burke, C.P., D.Ll. Jones (1995), Global radiolocation in the lower ELF frequency band, J.G.R., 100 (D12), 26,263–26,272.
89. Greenberg, E., C. Price, (2004), A global lightning location algorithm based on the electromagnetic signature in the Schumann resonance band, J.G.R., 109(D21).
90. Price, C., E. Greenberg, Y. Yair, G. Sátori, J. Bór, H. Fukunishi, M. Sato, P. Israelevich, M. Moalem, A. Devir, Z. Levin, J.H. Joseph, I. Mayo, B. Ziv, A. Sternlieb (2004), Ground-based detection of TLE-producing intense lightning during the MEIDEX mission on board the Space Shuttle Columbia, G.R.L., 31, L20107, doi:1029/2004GL020711.
91. Rafalsky V.A., A.V. Shvets, M. Hayakawa (1995), One-site distance-finding technique for locating lightning discharges, J.A.S.T.P., 57(11), 1255-1261.
92. Burke, C.P., D.Ll. Jones (1992), An experimental investigation of ELF attenuation rates in the Earth-ionosphere duct, J. Atmos. Terr. Phys., 54, 243– 254.
93. Boccippio, D. J., C. Wong, E. Williams, R. Boldi, H. J. Christian, S. J. Goodman (1998), Global validation of single-station Schumann resonance lightning location, J. Atmos. Terr. Phys., 60, 701–712.
94. Schmidt, C. T. (1993), Detection of distant lightning strikes from one location using Schumann resonances, M.Ph. thesis, Mich. Technol. Univ., Houghton.
95. Wilson, C.T.R (1924), The electric field of a thundercloud and some of its effects, Proc. Phys. Soc. London, 37, 32D-37D, doi:10.1088/1478-7814/37/1/314.
96. Franz, R.C., R.J. Nemzek, J.R. Winckler (1990), Television image of a large upward electrical discharge above a thunderstorm system, Science, 249, 48.
97. Boeck, W. L., and O. H. Vaughan, Jr. (1990), Lightning observations from the STS-32 space shuttle mission, EOS Trans. AGU, 71, 1241.
98. Sentman, D.D. and Wescott, E.M. (1993), Observations of upper atmosphere optical flashes recorded from an aircraft, G.R.L., 20, 2857–2860.
99. Lyons, W. A. (1994), Characteristics of luminous structures in the stratosphere above thunderstorms as imaged by low-light video, G.R.L., 21, 875– 878.
100. Boeck, W.L., O.H. Vaughan Jr. R.J. Blakeslee, B. Vonnegut, M. Brook, J. McKune, (1995), Observations of lightning in the stratosphere, J.G.R.,100, 1465-1475.
101. Heavner, M. J., D. L. Hampton, D. D. Sentman, E. M. Wescott (1995), Sprites over Central and South America (abstract), Eos Trans. AGU, 76(46), Fall Meet. Suppl., 115.
102. Sentman, D. D. (1996), Observations of red sprites and blue jets, Paper presented at 25th General Assembly, Union Radio Science International, Lille, France, July 1996.
103. Dowden, R. L., and C. J. Rodger (1997), Decay of a vertical plasma column: A model to explain VLF sprites, G.R.L., 24, 2765–2768.
104. Fukunishi, H., Y. Takahashi, A. Uchida, M. Sera, K. Adachi, R. Miyasato (1999), Occurrences of sprites and elves above the Sea of Japan near Hokuriku in winter, Eos Trans. AGU, 80(46), Fall Meet. Suppl., F217.
105. Hardman, S.F., R.L.Dowden, J.B. Brundell, J.L. Blahr, Z.I. Kawasaki, C.J. Rodger (2000), Sprites observation in the northern territory of Australia, J.G.R. 105, 4689.
106. Su, H. T., R. R. Hsu, A. B. C. Chen, Y. J. Lee, L. C. Lee (2002), Observation of sprites over the Asian continent and over oceans around Taiwan, G.R.L., 29(4), 1044, doi:10.1029/2001GL013737.
107. Yair, Y., C. Price, Z. Levin, J. Joseph, P. Israelevitch, A. Devir, M. Moalem, B. Ziv, M. Asfur (2003), Sprite observations from the space shuttle during the Mediterranean Israeli Dust Experiment (MEIDEX), J.A.S.T.P., 65, 635–642.
108. Neubert, T., T.H. Allin, E. Blanc, T. Farges, C. Haldoupis, A. Mika, S. Soula, L. Knutsson, O. van der Velde, R.A. Marshall, U.S. Inan, G. Sátori, J. Bór, A. Hughes, A. Collier, S. Laursen, Ib. L. Rasmussen (2005), Co-ordinated observations of transient luminous events during the EuroSprite2003 campaign, J.A.S.T.P., 67, 807-820.

109. Williams, E. R. (2001), Sprites, elves, and glow discharge tubes, Physics Today 41, 41– 47.
110. Pasko, V. P., U. S. Inan, Y. N. Taranenko, T. F. Bell (1995), Heating, ionization and upward discharges in the mesosphere due to intense quasi-electrostatic thundercloud fields, G.R.L., 22, 365–368.
111. Bell, T. F., V. P. Pasko, U. S. Inan (1995), Runaway electrons as a source of red sprites in the mesosphere, G.R.L. 22, 2127.
112. Milikh, G. M., K. Papadopoulos, C. L. Chang (1995), On the physics of high altitude lightning. G.R.L., 22, 85.
113. Roussel-Dupré, R., and A. V. Gurevich (1996), On runaway breakdown and upward propagating lightning, J.G.R., 101, 2297–2311.
114. Pasko, V. P., U. S. Inan, T. F. Bell, Y. N. Taranenko (1997), Sprites produced by quasi-electrostatic heating and ionization in the lower ionosphere, J.G.R., 102, 4529–4561.
115. Valdivia, J. A., G. Milikh, K. Papadopoulos (1997), Red sprites: Lightning as a fractal antenna, G.R.L., 24(24), 3169–3172.
116. Reising, S. C., U. S. Inan, T. F. Bell, W. A. Lyons (1996), Evidence for continuing current in sprite-producing cloud-to-ground lightning, G.R.L., 23, 3639–3642.
117. Hobara, Y., N. Iwasaki, T. Hayashida, M. Hayakawa, K. Ohta, H. Fukunishi (2001), Interrelation between ELF transients and ionospheric disturbances in association with sprites and elves, G.R.L., 28, 935–938.
118. Cummer, S. A. and U. S. Inan (1997), Measurement of charge transfer in sprite-producing lightning using ELF radio atmospherics, G.R.L., 24, 1731.
119. Bell, T. F., S. C. Reising, U. S. Inan (1996), Continuing currents determined from broadband ELF/VLF magnetic fields radiated by positive cloud-to-ground discharges associated with red sprites, EOS Supplement, 77, F61 (abstract).
120. Hu, W., S. A. Cummer, W. A. Lyons, T. E. Nelson (2002), Lightning charge moment changes for the initiation of sprites, G.R.L. 29(8), 1279, doi:10.1029/2001GL014593.
121. Hiraki, Y., T. Lizhu, H. Fukunishi, K. Nanbu, H. Fujiwara (2002), Development of a new numerical model for investigating the energetics of sprites, Eos Trans. AGU, 83(47), Fall Meet. Suppl., Abstract A11C-0105.
122. Williams, E. R. (2005), Lightning and climate: a review, Atmospheric Research, 76, 272-287.
123. Angell, J. K. (1986), On the Variation in Period and Amplitude of the Quasi-Biennial Oscillation in the Equatorial Stratosphere, 1951-85, Monthly Weather Review, 114(11), 2272-2278.
124. Jones, P. D., T. M. L. Wigley, P. B. Wright (1986), Global Temperature-Variations between 1861 and 1984, Nature, 322, 430-434.
125. Williams, E.R. (1989), The tripole structure of thunderstorms, J. G. R., 94, 13151-13167.
126. Hansen, J., A. Lacis, D. Rind, G. Russel, P. Stone, I. Fung, R. Ruedy, J., Lerner (1984), Climate sensitivity: Analysis of feedback mechanisms, In Climate Processes and Climate Sensitivity, J.,E. Hansen and T. Takahashi, eds.. AGU Geophys. Monograph 29, pp. 130-163. American Geophysical Union. Washington, D.C.
127. Lindzen, R.S. (1990), Some coolness concerning global warming, Bull. Am. Meteorol. Soc. 71, 288-299.
128. Rind, D., E. W. Chiou, W. Chu, J. Larsen, S. Oltmans, J. Lerner, M. P. McCormick, L. McMaster (1991): Positive water vapor feedback in climate models confirmed by satellite data, Nature, 349, 500-502.
129. Del Genio, A. D., W. Jr. Kovari, N. S., Yao (1994), Climatic implications of the seasonal variations of upper troposphere water vapour, G. R. L. 21, 2701-2704.
130. Sun, D. Z., I. M. Held (1996), A Comparison of modeled and observed relationships between interannual variations of water vapor and temperature, J. Clim., 9, 665-675.
131. Rind, D. (1998), Just add water vapor, Science, 28, 1152-1153.
132. Ksanfomaliti L. V. (1979), Lightning in the cloud layer of Venus, (in Russian), Kosmicheske Issledovaniya, 17(5), 747-762.
133. Ksanfomaliti L. V. (1983), Electrical activity of the atmosphere of Venus. I. Measurements on descending probes, (in Russian), Kosmicheske Issledovaniya, 21(2), 279-296.
134. Ksanfomaliti L. V. (1983), Electrical activity of the atmosphere of Venus. II. Satellite measurements, (in Russian), Kosmicheske Issledovaniya, 21(4), 619-633.
135. Ksanfomaliti L. V. (1985), Planet Venus, (in Russian), Nauka, Moscow.
136. Taylor W. W. L., F. L. Scarf, C. T. Russell, L. H. Brace (1979), Evidence for lightning on Venus, Nature, 279, 614-616.

137. Scarf F. L., C. T. Russell (1983), Lightning measurements from the Pioneer Venus Orbiter, G. R. L., 10(12), 1192-1195.
138. Eden, H. F. and B. Vonnegut (1973), Electrical breakdown caused by dust motion in low-pressure atmospheres: consideration for Mars, Science, 180, 962.
139. Melnik O., M. Parrot (1998), Electrostatic discharge in Martian dust storms, J. G. R., 103(A12), 29107-29117.
140. Farrell, W. F., M. L. Kaiser, M. D. Desch, J. G. Houser, S. A. Cummer, D. M. Wilt, G. A. Landis (1999), Detecting electrical activity from Martian dust storms, J. G. R., 104, 3795.
141. Renno N. O., A. Wong, S. K. Atreya, I. de Pater, M. Roos-Serote (2003), Electrical discharges and broadband radio emission by Matian dust devils and dust storms, G. R. L., 30 (22), 2140.
142. Bar-Nun A. (1975), Thunderstorms on Jupiter, Icarus, 24, 86-94.
143. Little, B., C. D. Anger, A. P. Ingersoll, A. R. Vasavada, D. A. Senske, H. H. Breneman, W. J. Borucki, The Galileo SSI Team (1999), Galileo Images of Lightning on Jupiter, Icarus, 142, 306-323.
144. Desch S. J., W. J. Borucki, C. T. Russell, A. Bar-Nun (2002), Progress in planetary lighting, Rep. Prog. Phys., 65, 955–997.
145. http://saturn.jpl.nasa.gov/multimedia/images/image-details.cfm?imageID=2001, 14.Feb.2006
146. Tokano T., G. J. Molina-Cuberos, H. Lammer, W. Stumptner (2001) Modeling of thunderclouds and lightning on Titan, Planer. Space Sci., 49, 539-560.
147. Lammer H., T. Tokano, G. Fischer, W. Stumptner, G. J. Molina-Cuberos, K. Schwingenschuh, H. O. Rucher (2001), Lightning activity of Titan: can Cassiny/Huygens detect it?, Planet. Space Sci., 49, 561-574.
148. Sukhorukov A. I. (1991), On the Schumann resonances on Mars, Planet. Space Sci., 39(12), 1673-1676.
149. Molina-Cuberos G. J., J. A. Morente, B. P. Besser, J. Porti, H. Lichtenegger, K. Schwingenschuh, A. Salinas, J. Margineda (2006), Schumann resonances as a tool to study the lower ionosphere of Mars, Radio Science, 41, RS1003, doi:10.1029/2004RS003187.
150. Besser, B. P., K. Schwingenschuh, I. Jernej, H. U. Eichelberger, H. I. M. Lichtenegger, M. Fulchignoni, G. J. Molina-Cuberos, J. A. Morente, J. A. Porti, A.Salinas (2002), Schumann resonances as indicators for lighting on Titan, Proceedings of the Second European Workshop on Exo/Astrobiology, Graz, Australia, 16-19 Sep. 2002, (ESA SP-518, November 2002).
151. Morente J. A., Molina-Cuberos G. J., Porti J. A., K. Schwingenschuh, B. P. Besser (2003), A study of the propagation of electromagnetic waves in Titan's atmosphere with the TLM numerical method, Icarus, 162, 374-384.
152. Molina-Cuberos G. J., J. Porti, B. P. Besser, J. A. Morente, J. Margineda, H. I. M. Lichtenegger, A. Salinas, K. Schwingenschuh, H. U. Eichelberger (2004), Shumann resonances and electromagnetic transparence in the atmosphere of Titan, Advances in Space Research, 33, 2309-2313.
153. Nickolaenko A. P., B. P. Besser, K. Schwingenschuh (2003), Model computations of Schumann resonance on Titan, Planet. Space Sci., 51(13), 853-862.