On Electromagnetic Precursors of Earthquakes: Models and Instruments

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Abstract: Although electromagnetic fields are well measured by electronic instruments today, they remain some what elusive in connection with earthquake phenomena. Some very good measurements and many well established connections have been made with larger earthquakes. However, the majority of studies do not give a clear cause-effect link between electric, magnetic and electromagnetic signals and earthquakes. Efforts to understand them better began almost three centuries ago [1]: first of all by means of electric fluid and electrical theory; secondly, by using Maxwell's equations; and thirdly, by approaching the problem with new orders of ideas. The importance of this challenge is twofold: first, it can help to throw light on the earthquake phenomena as a process that involves different forces in nature; secondly, it is a stimulus to find new approaches to recovering causality in this class of phenomena useful for a large number of types of interdisciplinary observations, including the Hessdalen phenomena.

Keywords: History of science, earthquakes, pre-earthquake phenomena, positive holes, ground currents, ground potential, magnetic emissions, electromagnetic emissions, Schumann resonances, ionosphere.

Introduction

Why we discuss electromagnetic emissions of earthquakes in connection with Hessdalen? Because the luminous phenomena observed at Hessdalen and many other parts of the world are similar to those observed before, during and after earthquakes [2]. Hence, because together with luminous phenomena other electric, magnetic and electromagnetic phenomena in connection with earthquakes were observed [3], it is interesting to study electric, magnetic and electromagnetic signals in the Hessdalen valley and in fact such signals have already been revealed [4].

Moreover, the problems faced in studying the Hessdalen phenomena are similar to those associated with the study of electric, magnetic and electromagnetic signals observed with earthquakes. They are: the necessity to obtain a continuous recording extended in space, because electromagnetic phenomena are usually well localized and unpredictable [5, 6, 7, 8]; the extraction of the signal from man made and natural noises [9, 10, 11, 12, 13, 14]; and the search of the source that is closely connected to the hypotheses for a model to understand the observations [6, 7, 8, 9].

Electric fields were probably observed by electrometers during the eighteenth century in connection with atmospheric instability during earthquakes [15] and successively by original radio receivers [16]; potential measurements stated values of about $10 \div 1000\mu V/m$ under low frequency [17].

The magnetic field was observed to be influenced by seismic activity even in the eighteenth century [18] and geomagnetic influence was shown with the strange movements of a compass during the nineteenth century [19]; modern recording quantified these variations to be about $1 \div 100nT$ in the ELF-ULF spectrum [20, 21].

Electromagnetic fields linked to earthquakes were studied, after Maxwell's theory had been formulated at the beginning of the twentieth century, as radio waves [22]. Together with the advance in communication technology many instruments became available to measure in any interval of the electromagnetic spectrum. Observations also showed anomalies in HF fields [23] while semiconductor sensors revealed infrared emissions from the surface of the earth from the future epicenters [24]. Electromagnetic fields yielded by charged particles motion were observed by means of particle physics instruments [25] to stress the interdisciplinary character of the earthquake process. Volcanic eruptions were also characterized by electromagnetic emissions; observations recorded from the eighteenth century underlined the recurrent manifestation [26]. Modern satellite observation confirmed electromagnetic anomalies measured on the ground to have scientific comparison in the neighboring space [27] while correlation of seismic events with precipitation of particles has been reported [28].

Luminous phenomena were probably the first electromagnetic phenomenon observed with earthquakes [29], by lightning for example or strange fires, auroras, rays and balls of light of different colors [30]. These phenomena are also to be found in many photos taken over the last 40 years [31]. In spite of repeated observations the science of these and other electromagnetic phenomena also associated with earthquakes is still controversial [32]. The first approach to understand them was linked to the electric phenomena of the atmosphere and it developed strongly in Italy [19].

Brief History

There were two reasons that this study flourished in Italy. First, Italy was repeatedly struck during the eighteenth century by devastating earthquakes

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and there were many opportunities to observe these facts. Secondly, in Italy there were many of the more important scientists who were at this time focused on electricity and electrical phenomena. Moreover, there was also a strong motivation to explain earthquakes because of the enormous suffering of the population.

With regard to earthquakes we can begin [33] with the event of Campania-Basilicata on 5 June 1688 with great shaking and 20.000 deaths. Destructive earthquake and a tsunami struck Sicily on 11 January 1693 with 93.000 deaths and again on 8 September 1694 in Avellino. A strong multi-fault earthquake struck L'Aquila-Norcia on 14 January 1703 with the death of 22% of the population. Then there were earthquake in Abruzzo-Majella on 3 November 1706, on 1 September 1726 once again in Sicily and on 12 May 1730 another time in Norcia, on 29 March 1732 once again in Avellino, on 24 April 1741 in Fabriano. Many earthquakes struck Tuscany in January 1742. On 20 February 1743 a violent earthquake struck Sicily, Calabria and Puglia, on 26 July 1751 Gualdo and Nocera in Umbria were shaken, Cagli in Marche was struck on 3 June 1781. A great earthquake with a tsunami and landslide struck Calabria on 4 February 1783 followed by a long seismic aftershock period which caused 60.000 deaths. On 25 December 1786 Rimini was struck and Camerino again in Marche was struck by a violent earthquake on 28 July 1799. At the beginning of the nineteenth century, on 26 July 1805, there was one in Molise.

The scientific study of earthquakes has a longer tradition but electric ones probably began in the eighteenth century, because a great number of observations were possible with numerous events also in Europe. We can remember the Lisbon earthquake on 1 November 1755 [15]. Parallel to Renaissance ideas in Italy a renewed interest for the earthquake phenomenon grew [34]; including strong experimental contributions to this topic inspired by the Galileian approach. A first Italian report that describes luminous phenomena was associated with earthquakes of Ferrara in 1570 [35]. Along line of Aristotelian thought, Father Nicola Longobardo (Caltagirone 1597 - Peking 1655) wrote a collection of recorded precursors that can be considered the seed of modern precursor study in Chinese earthquake prediction [34]. At the same time Father Francesco Maria Grimaldi (Bologna 1618 - 1661) began optical studies stating the first conclusion on the undulatory nature of the light, colors and diffraction phenomena [36]. In the middle of the eighteenth century the electrical theory of earthquakes in Europe was created, for which an earthquake was the result of an enormous electrical discharge in the crust in analogy with atmospherical phenomena. William Stukeley (1687 - 1765) was probably one of the first to sustain this interpretation in England and published a treatise on this argument in 1750 [37]. At the same time in Italy Father Andrea Bina (Milano 1724 - 1792) in Perugia attempted to explain earthquakes in analogy with Leyden's Bottle. He thought underground caves with sulphurous walls were like huge Leyden Bottles and intra-cavity channels were like conductors between them; a treatise was printed in 1751 [38]. Pierre Bertolon (1741 - 1800), in France, considered the idea of underground lightning and documented relationship between electricity and earthquakes in a philosophical treatise [39].

Major theories developed in Italy in those years [40] thanks to the work of great physicists such as Father Giovan Batista Beccaria (1716 - 1781) one of the principal experts in the theory of electrical fluids in Europe. King Carlo Emanuele III invited him to teach his new ideas at Turin University in 1748. Alessandro Volta (Camnago 1745 - Como 1827) and L. Lagrange (1736 - 1813) were his pupils. Arci-Priest Giuseppe Vannucci (1750 - 1819) was inspired by his teaching and wrote a report on phenomena associated with the Rimini earthquake and its interpretation [41]. At the same time Giovanni Vivenzio (174? - 1817) collected a complete series of observations on the earthquakes of Calabria up to the event of 1783 and wrote about it together with an interpretation [42]. The medical scientist Massimo Moreschini composed a document on the lack of equilibrium in the electrical fluid and its effects on the patients of the Camerino earthquake [43]. In 1799 Alessandro Volta discovered the electrochemical generator, but he also dealt with the study of electrical and chemical phenomena twenty years before. His interpretation of the strange fires was based on the atmospheric electricity primer of inflammable gas [44]. In the nineteenth century many collections were made. In Italy we had the contributions by Michele Stefano de Rossi (Roma 1834 - 1898), Father Alessandro Serpieri (San Giovanni in Marignano 1823 - Fiesole 1885), Torquato Taramelli (Bergamo 1845 - Pavia 1922) and Giuseppe Mercalli (Milano 1850 - Napoli 1914) [34, 45]. It was Father Alessandro Serpieri who created the first network of electrical signals associated with earthquakes by means of the telegraph network in 1873. Galvanometric anomalies [46] recorded in telegraphic stations were used to reveal earthquake events and station operators had to warn the network [47].

The tremendous catastrophe of the Messina earthquake in December 1908 gave new impulse to the study of electromagnetic anomalies because magnetic observations were made by a compass 12 hours before the quake [48]. And in 1909 numerous inventions were collected to reveal such signals [34]. U. Mondello detected self potential anomalies with his experimental apparatus before the occurrence of some earthquakes [49]. Father Raffaello Stiattesi (18?? - 1932) performed several experiments to obtain a device to reveal electromagnetic signals with greater sensitivity and began to warn the population of imminent earthquakes by two red lights from his observatory tower; he spoke about another three scientists that worked on this research [48]. One of these was U. Mondello, another was Father A.

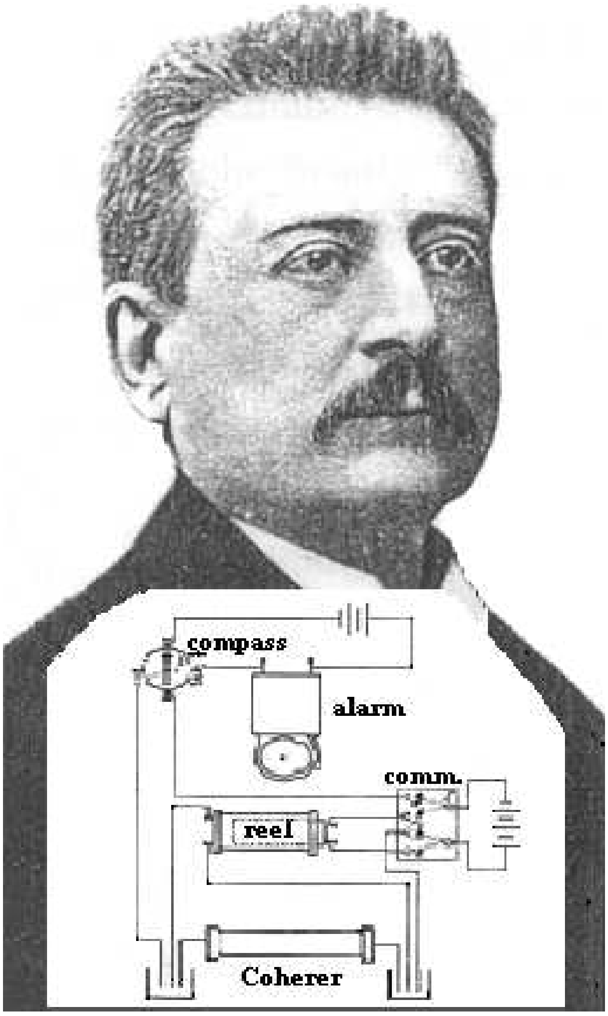

Figure 1: Simple scheme of earthquake adviser by the Coherer in 1887 with his author Temistocle Calzecchi-Onesti.

Figure 2: Giuseppe Ceramicola and his electro-seismic adviser in 1917.

Maccioni who detected radio signals linked to earthquakes by using a slightly modified version of the "Coherer" [50], invented by Temistocle Calzecchi-Onesti (Lapedona 1853 - Fermo 1922) in 1887 and already used by him to build a new seismic adviser [51], see figure 1. The other, see figure 2, was Giuseppe Ceramicola (Pergola 1879 - Ancona 1951) who realized an instrument for earthquake forerunners by means of the electro-mechanical effect [52]. Engineer A. Prati put Maccioni's device to a commercial use [34], while E. Ungania supported the use of such a device throughout Italy to forecast earthquakes [53]. Another active supporter of this research was Father Guido Alfani (Firenze 1876 - 1940) which used his friend Guglielmo Marconi's radio receivers to synchronize his seismographs by the time signal of the Eiffel Tower [54]. In the same period Father Ignazio Galli (Velletri 1841 - Roma 1920) published the first collection of observations of luminous phenomena in connection with earthquakes [30]. He was the first scientist to classify these phenomena.

However, in the same period in Italy, a movement opposing the forecasting and all of the precursory phenomena associated with earthquakes was born. The forecasting warnings attempted by Stiattesi were forbidden by the legal authority with the motive that it would create alarm among people, while his studies were abandoned because of financial problems [55]. From that period up to now such research has been strongly criticized and opposed, even though a serious and in depth study of this topic is still missing, as no true scientific motivation exists. So what was the reason for?

The danger of a false alarm was used to justify this anti-research earthquake study movement, but in my opinion this was not the real motive. The true reason was linked to the particular response of the Italian scientists to the positive approach that science unconditionally "embraced" during the nineteenth century in Europe [56].

On the one hand, ideas based on well ascertained experimental facts of seismology [34] were based on the long tradition of instruments [57] and the well accepted theoretical bases of inertial mechanics [58], so positivism found fertile ground in the Italian seismological world. On the other hand, the electromagnetic approach was only at the beginning of a complete theoretical formulation, using the Maxwell theory as well as chemical, biological, etc. At the same time earthquake observations and research was already interdisciplinary and precursory oriented in Italy [34], but there were no complete catalogues or ordering at the end of the nineteenth century for other phenomena associated with seismic events. Researchers were groping along with no standard instruments in connection with non seismic phenomena at that time [59]. Thus new formulated ideas on earthquakes would not have been positive and scientific production of those new studies can not compete with respect to the positive appreciation of seismic ones.

Figure 3: Raffaele Bendandi in a photo of the Progresso Italo Americano on 1 January 1928.

Further, as we have seen major supporters of these studies were religious members of the Church in Italy, i.e. the religious scientists from which there were fundamental and original contributions. However positivism marked a net separation between science and religion, so that action was taken to discredit religious scientists and their studies together [60].

Finally it should be made clear that forecasting attempts were also made by means of the various types of seismographers at that time, but without results that can sustain further studies [61]. So if true science is positive like seismology and through seismology it is not possible to forecast earthquakes then earthquake forecasting is impossible as a positive principle itself. This is the reason why many scientists working on this topic met with such strong opposition and the distrust there is today has its roots in what has just been mentioned.

Raffaele Bendandi figure 3 (Faenza 1893 - Faenza 1979) gathered the ideas of all Italian scientists without prejudice because his self taught approach protected him from complete acceptance of positivism. He initially met no opposition because of his contribution to the seismological detection of earthquakes and his affiliation to the seismological society of Italy [62]. He studied the relation between electromagnetic interferences, earthquakes and solar activity in depth, by means of radio-telegraph stations, see figure 4, radio-receivers in medium and small waves, compass, seismometric instruments and a telescope. He proposed that a new order had to be used to view these phenomena, in which a unique cause was at the source of them so that the succession of manifestations of seismic, electromagnetic and solar phenomena can not be the same every time [63]. He spoke of gravitational disequilibrium as the universal cause and earthquakes not as local but global phenomena [63], then began his forecasting known in the entire world [63]. At the same time Italian scientists isolated him and condemned earthquake forecasting because of the danger of frightening the population [64], but no study was conducted to verify such an idea then and neither today. Why has this unscientific behavior continued up to today?

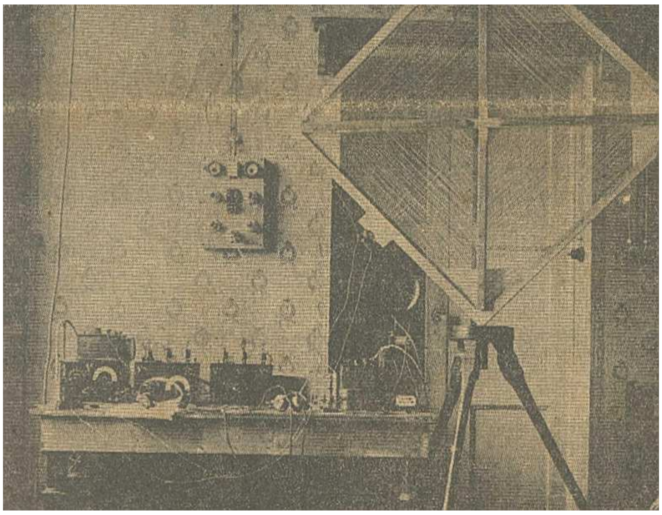

Figure 4: The radio-telegraph station of Bendandi's observatory in 1935.

The reason is in the new motivations raised in the last half century that have sustained the seismic approach. One of these seemed to be the possibility of the know-how transfer from research to the engineering applications of buildings [34] that further supported seismology study. At same time many seismologists denied the possibility of forecasting earthquakes and existence of the premonitory phenomena because of their inability to forecast earthquakes through seismology.

On the other hand, when the necessity to obtain funding was dependent on international scientific acknowledgement and prestige, seismological research offered secure bases and support of older approaches became more important than encouraging news.

Again, we should recognize that condemnation of forecasting produced a silence on the topic, dampened the mystery of the phenomena and sustained fear among people.

The utility of this brief history may be to understand the problems faced by those studying the Hessdalen phenomena, those disinterested in them and the lack of support for this type of study. As a matter of fact, an experimental observation was very difficult. These phenomena were never positively accepted, in the same way as non seismic phenomena, because of the "selectivity effect" of positivism which decided what the "true" phenomena are.

Instrumental Measurements

Science needs to quantify some aspects of the phenomena for a comparison of different observations from different scientists and their confirmation. In modern science we can realize measurements of magnetic and electric fields that are not strictly linked near the stationary case. In this case, for example, the electric field induced by the magnetic field is roughly proportional to the ratio δ/λ of the magnetic field, where the skin depth $\delta \ll \lambda$ is the wavelength of the field [65]. In the non stationary case, instruments can evaluate electromagnetic waves by means of the amplitude of electric or magnetic fields independently. Many instruments are available today which work better in a narrow region of the spectrum. Antennas with several types of amplifiers are used up to the UHF band while semiconductor sensors can be used from the IR to UV light. Emissions and precipitations of charged particles can also be linked to earthquakes [66, 67] and they are revealed by several types of particles counting [28]. Other electromagnetic instruments can be used to evaluate their quantities of energy, momentum and mass.

Magnetic signals can be evaluated by proton precession magnetometer. It operates on the principal that the protons in all atoms, for example in Hydrogen atoms of distilled water, are spinning on an axis aligned with the magnetic field. When subjected to an artificially-induced magnetic field, the protons will align themselves with the field. When this field is interrupted, the protons return to their original alignment with the earth's magnetic field. As they change their alignment, the spinning protons precess, or wobble, much as a spinning top does as it slows down. The frequency at which the protons precess is directly proportional to the strength of the earth's magnetic field. This is the Proton Gyromagnetic Ratio, equal to $0.042576Hz/nT$. For example, on the surface of the earth with field strength of $57,780nT$, the frequency of precession would be approximately $2460Hz$. This instrument measures the scalar component of the field i.e. the total amplitude, sensitivity go down to $0.1nT$ and show no appreciable instrumental drift [68].

The flux gate magnetometer working principle is based on the phenomenon of magnetic hysteresis. The primary element is made of two bars of highly magnetic permeability material. A magnetizing coil is spooled around the two bars in an opposite sense so that the magnetic field created along the two bars will have opposite polarities but the same intensity. A secondary coil wound around both bars will detect an induced electric potential only in the presence of an external magnetic field. This instrument measures the vectorial component of the field i.e. the amplitude relative to the direction of sensor, sensitivity goes down to $0.01nT$ [27].

Coil magnetometer is adapted to the vectorial measurement of magnetic fields and is used to reveal magnetic variations. Sensitivity goes down to the noise level of $4fT/\sqrt{Hz}$ at $6KHz$ [69], while the SQUID version with superconductive coils from DC to $1MHz$ goes down to $40fT/\sqrt{Hz}$, $1/f$ corner at $10Hz$ [70].

Electric fields are in the atmosphere but can also be measured in the crust [71] and sea on ELF spectrum [72]. Methods are different depending on dielectric and frequency. From DC to LF electric fields can be measured by field effect amplifiers connected to appropriate antennas. Sensitivity is strongly linked to the frequency of the signal and the geometrical characteristic of the antennas, in Demeter mission it goes down to $0.2\mu V/\sqrt{Hz}$ at $500KHz$ [73]. DDP measurements are used to evaluate underground electric fields by means of voltage measured between two electrodes, sensitivity go down to $0.1 \div 1\mu V$ [27]. Radio receivers can also be used to evaluate electric fields but only as a comparison method because of their non linear response. They can give an indirect measure of absorption in atmosphere or variation of the sub-ionospheric channel [74].

What about luminous phenomena? Study is at the beginning and one can make several types of measurements, for example luminosity as a measure of intensity of the field in W/m^2 by photometers. The sensitivity can be very strong with some apparatus capable of revealing single photons from particle physics devices [75]. Space-time geometry can be quantified by video taping luminous appearances and their topological analysis, definition in time being up to *msec* and any spatial one can be obtained [76]. Spectral content can be revealed by means of optical devices with the great precision of astronomical technology, giving information on emissions, absorption and the Doppler effect linked to the objects temperature and movements [77]. Infrared instruments are already supported by mature technology with a very high level of sensitivity [78]. In the past only infrared studies were possible and indeed a fortuitous result of meteorological instrumental apparatus was obtained via satellite monitoring [24] because of the big extension of emission. Even more infrared recordings could be possible at a low cost in Hessdalen. They would be interesting because of the precision reached by technology. Quantitative detection of the luminous effect associated to earthquakes has not been done up to now because of the rarity of the phenomenon and high anthropogenic noise level, together with highly expensive instruments. A complete quantitative detection of the luminous Hessdalen phenomena's lacking although a high frequency of sightings at the same place have been noted. This can be a consequence of a lack of instruments because sufficient funds were not readily available for this study. However, recent applications to geophysics have been made in connection with luminous atmospheric phenomena [76]. It is possible that in a short time such apparatus will be useful to study the Hessdalen phenomena in depth.

On the other hand electromagnetic phenomena were measured on several occasions and a quantitative estimation of them is available today. They state that magnetic fields manifests themselves as anomalies between $1nT$, for small events (M=2) and instruments near the epicenter [79], and more than $200nT$ for big events [80]. Limitation in this case regards solar and geomagnetic effects that prevent any useful recording during the periods of strong activity with noise level up to $400nT$ [81] while such noise goes down to few pT during calm periods and $1/f$ noise dominates at low frequencies. Electric field measurements are also impossible in some periods, for example when atmospheric perturbations happen with thunderstorms or charged clouds come near the instruments the electric field can reach about $1KV/m$ [82], but even geomagnetic bursts can generate DC gradients of potential about several V/Km. On calm days natural noise goes down under $1mV/m$ but because of anthropogenic noise many scientists consider a threshold of about $10mV/m$ to detect a suitable signal and in fact electric field amplitude from $100mV/m$ to $1V/m$ has been measured in connection with earthquakes [83, 84]. RF signals monitored from low to high frequencies have amplitude of about $10 \div 100mV/m$ [85].

Models

Electric and magnetic sources were studied in connection with the early stage processes of earthquakes [86]. So, if we think of the hypocenter as the zone over which tectonic stress is concentrated, then the consequence of this stress is the separation of charge and the production of an electric field while movements of charge produces magnetic fields. Thus electromagnetic emissions are the consequence of separation and recombination processes. Several hypotheses to explain the separation of charge in the rock have been presented over the last half century and a mathematical formulation has been developed for all of them [87].

For example the piezoelectric effect [88] could be responsible for an electric field whose relationship with stress, strain and polarization are defined by

$$\begin{aligned} D &= P_{D\sigma}\sigma + P_{DE}E, \\ \varepsilon &= (P_{\varepsilon\sigma})^{-1}\sigma + P_{\varepsilon E}E, \end{aligned} \tag{1}$$

where $P_{\varepsilon\sigma}$ is the Hooke's tensor, P_{DE} the dielectric tensor and $P_{\varepsilon E} = P_{D\sigma}$ are the piezoelectric tensors. Unfortunately no obvious link was developed between earthquakes and electric manifestations because the major rocks do not contain high percentages of piezoelectric crystals and such crystals are casually oriented so the net contribution of to a portion of crust is small. Moreover resistivity measured in the crust is small compared with what is necessary to maintain separation of charge [89]. A unique possible way to explain observed electrical activity seems to be the critical behavior of rocks before earthquakes [88].

When we observe magnetic anomalies we can think about the piezomagnetic effect [90] on the magnetization of the rocks. For example relations between stress σ and magnetization ΔH can be described by the tensorial relation

$$\Delta H_k = \frac{16\pi}{9Z}(\sigma_{ij}\sigma^{ij})^{\frac{1-n}{2}}\bar{\gamma}^{ij}_{kl}J^l\Delta\dot{\varepsilon}_{ij}, \tag{2}$$

where the strain variations depend on a power of stress obtained by a "stress sensitivity exponent" $\dot{\varepsilon} = Z\sigma^n$, J is the initial magnetization and γ is the piezomagnetic tensor and Z is a constant. Problems concerning the numerical calculus of the magnetic field produced from a dislocation for which values are smaller when measured [91]. Also motivations by temperature variation near the Curie point in the volcanic region should be unexplainable because of the incompatible velocity.

Movements of water observed before earthquake inspired electrokinetic phenomena as a cause of electromagnetic anomalies. It can be described in analogy with a capillary flux of liquid [92], in a first approximation, as

$$\begin{aligned} I &= -(\phi/\rho)\nabla E + (\phi\epsilon\zeta/\eta)\nabla P, \\ m &= (\phi\epsilon\zeta/\eta)\nabla E - (\rho/\eta)\nabla P, \end{aligned} \tag{3}$$

where I and m are respectively the current and fluid flux, P the pressure, η the viscosity, ζ the "zeta potential", ϱ the permeability, ϕ the porosity, ϵ and ρ the dielectric constant and resistivity. Such a description together with a fault model [93] could be the cause of the signal observed only in severe conditions of fluid pressure and separation.

Separation of charge can also be possible by fracturing the piece of rock because of a microscopic dislocation that divides the electrical charges. Friction can be responsible for producing charge by the triboelectric effect. Chemical reactions can release free charges of one type. In connection with these effects electromagnetic radiation can be emitted by mechanical conversion, induction of currents in the medium and variation of resistivity. Thermo and piezo currents were hypothesized in connection with the variation of temperature and pressure with respect to the curie point. Magneto-hydro-dynamic is active in conductive fluids like the sea and the ionosphere. Many other mechanisms to generate electromagnetic signals were evaluated but none of them were suitable to describe all electromagnetic manifestations while all of them need particular critical conditions to explain observed amplitude of signals [87]. This is also because of the big absorption of the crustal medium that separates source from instruments.

We can start studying these phenomena by defining the electromagnetic characteristic of the crust and geophysical medium by the quantities which are dielectric and magnetic constants and conductivity and mobility of charge [94]. In a simple discussion we might neglect the last characteristic of the medium that influences the spectral content of the signal and evaluates the screen depth of the crust with a simple model of the electric stratification of the crust. We can observe that also through few kilometers of crust fields amplitudes are reduced strongly [87]. Scientists have worked out some hypotheses to explain the possibility that signals can emerge out of the crust if the source is in the hypocenter. So a special stratification was included in calculus, but yielded no better results for the amplitude of signal [95]. Stratifications to realize a wave guide or a strict conductive channel were considered. In this way the medium absorbs the signal as a power of the distance and produces amplification of the amplitude of the field near the edge of the channel [96], but constitutes special conditions.

We should note that the current approach is based on three steps: the first consists in the generation of the electromagnetic field in the hypocenter; the second is where such an electromagnetic field goes through the crust; in the third, the electromagnetic field interacts with the instruments. But no observations confirm this order of events: a sequential order. Together with this observation we should remember the works by Ezio Mognaschi on rocks fracture [97] and electromagnetic propagation [98] with some experimental results recently obtained [99], to also stress the necessity to study the sequential order of view in depth.

New Models

In a new approach, instruments are near the source or are in the source of electromagnetic signals, this can overcome the difficulty in measuring weak signals from the hypocenter.

Many anomalies of the propagation medium were observed before earthquakes happened such as variations of rock resistivity [100], movements of conductive liquids in the crust [101] and altitude changes of the ionosphere [102], so that induction can be modulated and mode selection can be modified sustaining the idea that propagation medium behavior is like a source itself [103].

In this view of phenomena associated with earthquakes the electromagnetic ones are the manifestation of a larger process, no more a step of the succession of phenomena sustained today [87]. Different manifestations should also be considered together in this approach because they are observed together in the periods and in the regions of earthquakes. They are projections of the same order in multidisciplinary aspects of nature. Sequential order is not the best way to understand this process. However, we will describe some simple examples in depth to improve clarity before proposing different and more suitable order.

a) Schumann resonances

Schumann resonances are natural electromagnetic phenomena of the Earth-ionosphere cavity which were predicted by W. O. Schumann in 1952 [104]. Their frequency spectra are known to be very stable and, recently, abnormal behavior in Schumann resonances has been observed in possible relation to earthquakes in Taiwan [105]. The fourth harmonic of the Schumann resonance resulted strongly enhanced up about 40% as the most significant difference from the conventional case, while a significant frequency shift of its peak frequency of about $1.0Hz$ from the conventional value was observed. All inland earthquakes with $M \geq 5$ were found to have been characterized with the anomalous Schumann resonances while not all oceanic earthquakes were [105].

In the present example we will consider such abnormal behavior as the source of electromagnetic anomalies without emphasis to the link with earthquakes. In other words the variation of frequency and amplitude of Schumann resonances will be analyzed to obtain the correspondent behavior in time of an electric or magnetic signal for an evaluation of the Earth-ionosphere cavity as a source of anomalous signals.

As a simple exercise we consider the case where the oscillations of both the amplitude and frequencies of resonances being lower than the oscillations at resonance. The daily modulation of frequency shift, which is thought to depend on the Earth rotation through the solar wind, offers a condition where perturbations can be considered near stationary. Frequency of modulation is $f_D = 0.000023Hz$ which is several orders of size less than the first resonance $f_1 = 7.8Hz$, as well as solar proton events are suitable examples being about several hours long and X-ray burst [106]. In this case we can consider Schumann solutions in the stationary case and shift them by a small amount.

ELF spectra in nature can be understood by means of a casual contribution to the electromagnetic field generated by about 2000 thunderstorm cells permanently active around the Earth, which produce approximately 50 lightning events every second [108]. The result of this casual stimulus is a distribution of electromagnetic energy near the resonances which are revealed for a magnetic or electric field [109]. We can attempt to fit this distribution by a Lorentzian [106] and calculate the inverse Fourier transform to obtain the temporal evolution of the signal, see Appendix a). In the approximation of near stationary variations of the resonances $f_n = f_n(t)$ and time shift can be shown in figure 5.

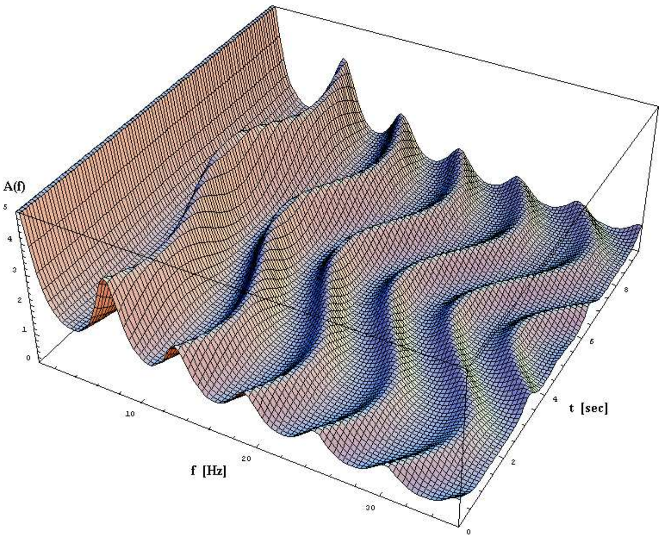

Figure 5: The dynamical spectrum of the Schumann resonances with a sinusoidal shift of 10% in frequency plus $1/f$ noise, we can also observe amplitude modulation.

Mode frequency in general depends on the dimensions of the cavity. In this example the essential dimension of the natural Earth-ionosphere cavity is the height that separates the Earth's crust from the ionized layer of the atmosphere. So we can think of such height variation to explain mode shift and write resonances as functions of their height $f_n = f_n[h(t)]$. However, such an interpretation reveals itself to be naive and insufficient to understand the shift observed. Dependence on the ions concentration of the ionosphere must be introduced by thinking of a distribution of ions with height [106]. This means that the ionosphere is not a perfect conductor and dissipation of energy manifests itself with a reduction of the resonant frequency from the ideal results. Even if this progress is a good understanding of frequency modulation, strong amplitude modulation remains a mystery [107].

One approach understanding electromagnetic signals of earthquakes consists in a model where the ionosphere over the epicenter modifies concentration of ions before shaking and, in this way, modifies the boundary conditions of the cavity and mode selection. In this way instruments are inside the source itself!

However, even if a variation of concentration of ions can explain differences in recorded anomaly, a slow modulation of them seems insufficient to explain electromagnetic anomalies associated with earthquakes, see Appendix a). Various attempts to model recorded signals before earthquakes by different concentration functions with slow dependence on time failed to reproduce them. In figure 6 the time evolution of the amplitude of the electromagnetic field is shown, which was simulated by a remote source of 30 lightning events every second where the abnormal modulation of about $1Hz$ is about 50% in frequency, see Appendix a). Variation of this signal is not important if calculated from the effects mentioned above.

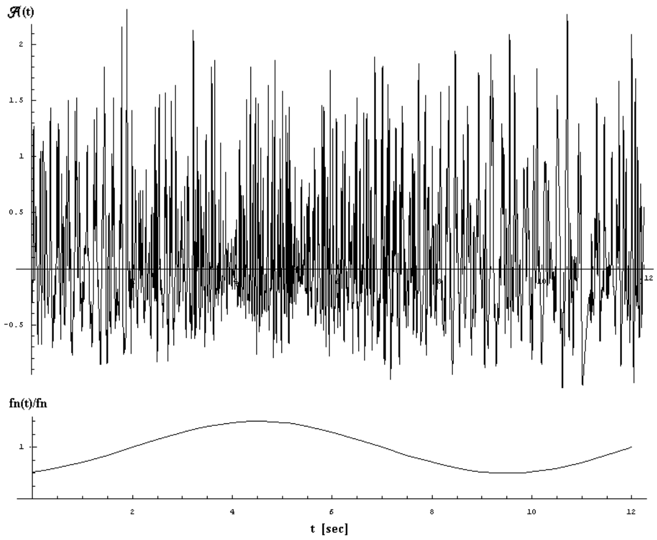

Figure 6: The temporal evolution of the field amplitude produced by random generated source lightning.

Before rejecting this interpretation it is important to underline that it is a rough approximation and is not valid for more interesting cases that happen in the conditions where perturbation frequency is near the resonances. When the variation frequency of the parameter of the perturbation, the ionic concentration and their height in our case, is near a resonance of the cavity we can obtain a parametric amplification of the resonant field. This system is a parametric oscillator [110]. The parametric oscillator in electromagnetic systems has shown interesting effects in connection with quantum optics in a cavity where there are moving walls, because of the possibility to enhance intensity of the field [111].

The analysis of the parametric oscillations in the Earth-ionosphere cavity presents major difficulties because the three-dimensional problem is not simply reducible in a single dimensional one [112]. Further analysis must also consider local variations of the ions concentration [113].

b) Positive holes

This second example concerns a precise physical effect of the preparatory stage of earthquakes. It consists in positive holes emission by the region around the hypocenter of a future shock [114, 115].

In a situation where free charges are activated on

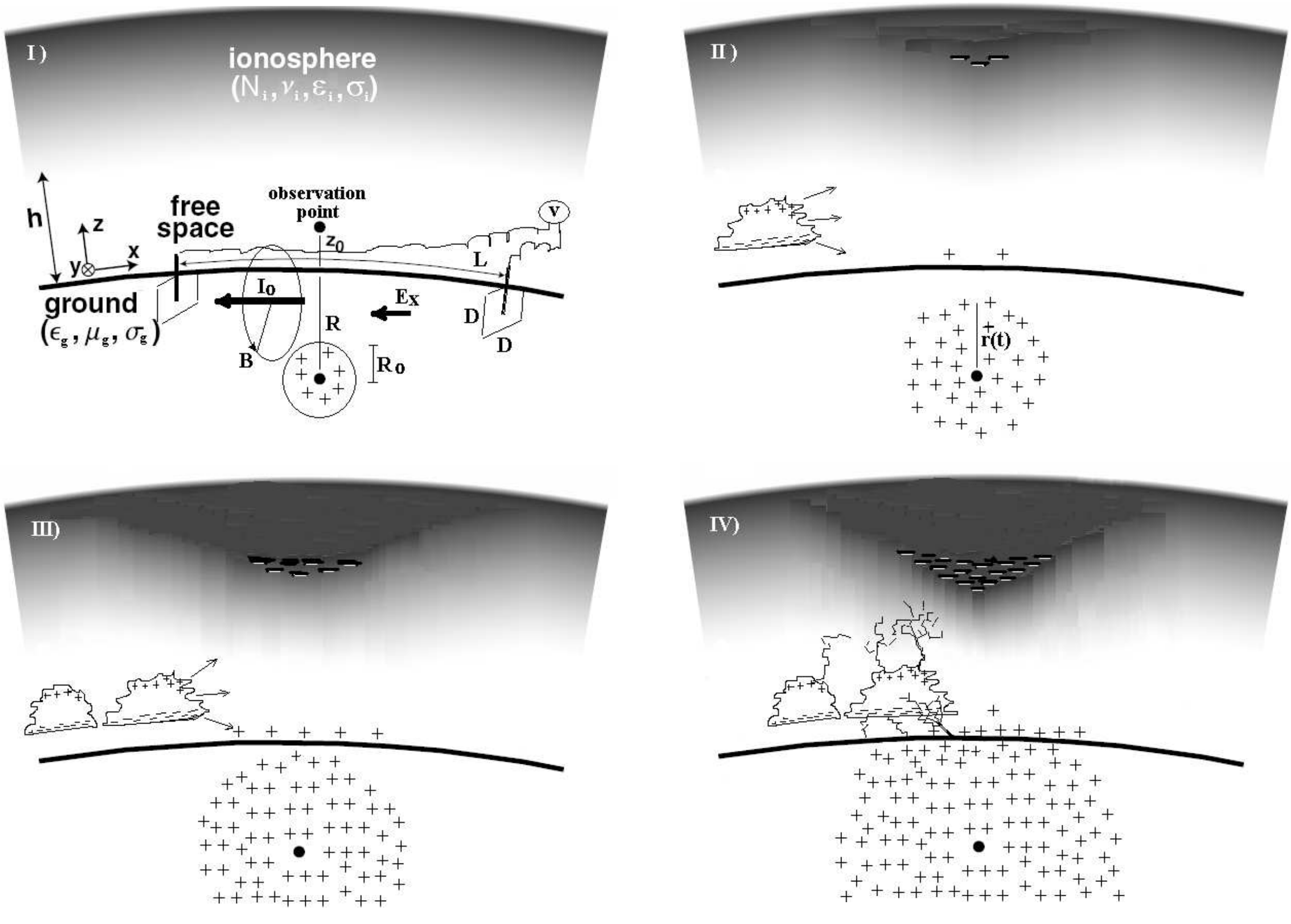

Figure 7: Four step sketch to visualize mouvements of the charges associated to earthquakes; sizes of scale of the phenomena are not the same.

the hypocenter or in the crust near the hypocenter we can imagine that these free electrical carriers increase the conductivity of the crust and contribute to the induction of the electric signal. Fields are also modified because of the modulation of telluric currents. Their movement toward the surface modifies electric potential with respect to the ionosphere and because free carriers are positive holes the electric field increases. Free electrons in the ionosphere are attracted to the region over the future epicenter further increasing Earth-ionosphere potential. Associated with emitted positive charge on the surface are recombination processes while the high gradient of potential produces discharges, both of which can show several luminous effects. Schumann resonances are also modified because of the variation of ions concentration as underlined above. Further influence of modified electrical potential on the magnetosphere particles motion can inspire an understanding of manifestation of particle precipitation. The charged clouds near the epicenter feel the effect of greater electric potential between the Earth and ionosphere being attracted by it. The arrival of charged clouds is like the interposition of electrical dipoles in the cavity that increases the electric field even more with the manifestation of lightning and thunderstorms. RF electromagnetic signals generated underground by the fracture of rocks are strongly damped from the ground but they can also be emitted in atmosphere by electrical discharges. A simple sketch of the process is shown in figure 7.

To evaluate this model we should attempt to quantify the effects of this process on electric and magnetic fields measurable on the ground, beginning with the electrostatic field generated by an emitted positive charge near the hypocenter. Positive holes in the ground will induce a polarization in the crust and will induce negative charge to accumulate in the ionosphere on the hypocenter. So the electric field will be directed prevalently upward and its modulus will be a contribution of the holes emission plus the contribution of the increase in the ionospheric electron concentration.

If Q is the total amount of charges produced in the ground then in a simple model we can express the electric field measured at $(0, 0, z_o)$ on the Earth surface as

$$\mathbf{E} \simeq E_o\hat{k} + \frac{Q(\varepsilon_g, \sigma_g)\hat{k}}{4\pi\varepsilon_o(R+z_o)^2}, \tag{4}$$

where E_o is the constant electric field produced by normal Earth-ionosphere difference of potential σ_g is the conductivity of the ground, with R equal to the depth of the hypocenter, that was supposed to be the holes distribution center, and ε_g the dielectric constant of the ground, see Appendix b).

Near the stationary conditions, for slowly producing and moving density of charges the electric field can be obtained with $Q = Q(t)$ in (4). Supposing that before earthquake charges are emitted by a portion of the ground, the total charge increases and it is all that we need to know to evaluate the electric field on the surface. If we consider a hypocenter at $R = 10Km$ which produces a rate of $d\rho(t)/dt = 10^4 A/Km^3$ [116] in a volume of radius $R_o = 4Km$ then $I_o = 2.6810^6 A$, the electric field on the epicenter at $(0, 0, 0.1Km)$ for $\varepsilon_g = 20\varepsilon_o$ and $\sigma_g = 10^{-7}\Omega^{-1}m^{-1}$ will have the direction upward with the maximum value of about $4V/m$. A better evaluation of the electric amplitude should be made considering atmospherical electric currents [117, 118] For $x_o \neq 0$ and $y_o \neq 0$ a horizontal electric component will have a direction outward from the origin and can be calculated by the relation in the Appendix b).

The same model can also be used in a complementary mode, when an excess of charge appears in the atmosphere. This can be the case when concentration of the ionosphere is modified by solar burst or the particle precipitation [119, 120].

Another interesting chapter of study is the effect of the variation of conductivity of the crust on the induction of electric fields by variable magnetic fields [121]. Now, with reference to figure 7 I), we consider two electrodes buried in the ground to such a distance $L \ll R$ so that the front of positive carriers can be considered flat. In this case we can define mean resistivity $\bar{\rho}$ of the conductive channel partially invaded by holes, see Appendix c). If the propagation velocity of holes is such that $\bar{\sigma} = \bar{\sigma}(t)$ changes slowly with respect to the oscillations of the magnetic field, $t \gg 1/\omega$, we can evaluate the effect on the horizontal electric field. With the conductivity produced by the holes being $\sigma_h = 10^{-3}\Omega^{-1}m^{-1}$ we obtain a decreasing value of E. However, if we consider that arrival of the holes can be associated to recombination with free electrons then resistivity will be increasing at beginning with a resulting peak of the electric field.

On the other hand, when a constant gradient of potential is present on the surface and in the ground telluric currents flow in the crust. Such currents are proportional to the conductivity of the crust which can modulate them. Electric currents generate magnetic fields which we will attempt to calculate.

If a constant electric field $E_x = -100mV/m$ is present in the region of the epicenter we can write the density of the telluric current $J(t) = \sigma(t)E_x$ and magnetic induction can be evaluated in the simple model purposed in the Appendix c) by considering moving holes at velocity equal to $100m/sec$ [115] with conductivity $\sigma_h = 10^{-2}\Omega^{-1}m^{-1}$ and $\sigma_g = 10^{-7}\Omega^{-1}m^{-1}$. The horizontal magnetic field at $(0, 0, z_o)$ reaches values about $10pT$, see figure 8.

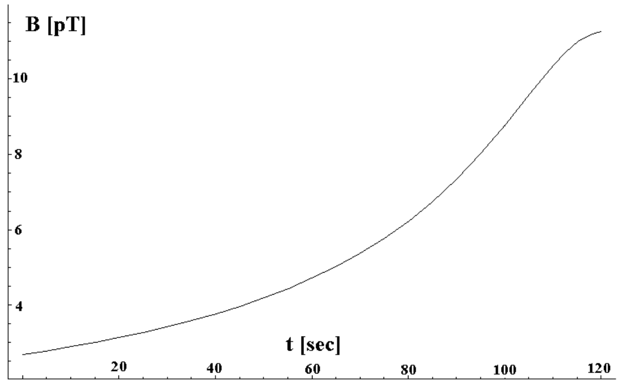

Figure 8: Time evolution of the magnetic induction above the surface produced by the diffusion of the holes.

Conclusions

One approach establishes that electric, magnetic and electromagnetic fields arise from the hypocenter during the preparatory state of an earthquake and propagates through the crust, atmosphere and sea to interact with the instrumental settings, although no observations support such a succession of events.

Two simple models near the stationary case were discussed which consider sources of electric, magnetic and electromagnetic fields near the instruments or comprising the instruments themselves. This is possible because they are big as much as to comprise hypocenter, epicenter and atmosphere above them, then it is unnecessary to consider the process of revelation of the fields in three sequential steps: generation, propagation and interaction with instrumental settings. In fact generation and interaction happen together and lose their means as separate phenomena while propagation is not required. So electromagnetic anomalies associated with earthquakes can be seen as a whole process no longer divisible in steps. This approach is based on the same line of thinking which appeared during the first half of the twentieth century in Italy and today offers the main advantage to understand several manifestations in a unique model.

Order which emerge from these studies seems to be of the kind called “generative order” [122], by it is possible a non-mechanical approach to the pre-earthquake phenomena [116].

Variations of boundary conditions of electromagnetic phenomena in the planetary system offer an example such as Earth-ionosphere cavity. Discussion of the problem near the resonance is needed to verify its relevance so as sustained for other earthquakes influences [28].

Hole activation presented the better link between earthquakes and electromagnetism to understand so many phenomena. It can generate strong electric fields, contribute to electric and magnetic induction by the conductivity modulation of rock, explain manifestations of lightning and thunderstorms, Schumann resonance variations, ionosphere modifications and many other observations as stressed by the author [123]. With this interpretation it is possible go beyond the propagation problem of damping of the crust [124]. Another principle characteristic of this idea is to introduce electromagnetic emission in a standard model of earthquakes [114]. The same approach can be sustained with the movement of fluids in the crust because these are the boundary conditions that select electromagnetic modes and modulate resistivity. All of these examples need to be considered in the non stationary case to obtain a better estimate of them.

What about the Hessdalen phenomena?
Two recent experiments resume the idea of plasma. One by microwave drilling that concentrates power on a layer of solid materials [125]. In this case the author thought that a cloud of plasma and metallic dust was the cause of ball lighting. The other experiment by electrical discharge in water [126]. In this experiment the author sustains that a cloud of ionized hydrogen and oxygen was the cause of ball lighting. Models analyzed in this report imply high electric potentials and sustain the possibility that ball light observed in connection with earthquakes has this origin. However there still remains a mystery: what are the forces that link the plasma phase? Is perhaps wholeness an approach that leaves any possibility to answer this question?

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Appendix a)

According to other works [106] we suppose that the spectrum of Schumann resonances is like

$$A(f) = \sum_n \frac{A_n}{\frac{(f-f_n)^2}{\Delta_n^2} + 1}, \tag{5}$$

where A is the amplitude of the electric or magnetic field, with the opportune choice of the constants A_n and Δ_n we can fit the function to a recorded value of the spectrum. With reference to the magnetic field value reported in [108] we chose an $A_n = A_o f_n^{-1/m}$ gaining $m = 1$.

To estimate the width of the Lorentzian we can impose that

$$\frac{A_o}{f_n} \frac{1}{\frac{(f_{n+1}-f_n)^2}{4\Delta_n^2} + 1} = \frac{B}{f_n}, \tag{6}$$

where B/f_n is the $1/f$ noise. Then is possible to obtain

$$\Delta_n = \sqrt{\frac{B}{A_o - B}} \frac{f_{n+1} - f_n}{2}. \tag{7}$$

Further comparisons with the curve in [108] suggested $A_o = 24$ and $B = 5$. The inverse Fourier integral can be resolved to give the temporal evolution of the signal written as

$$\begin{aligned} A(t) &= \frac{\pi}{2} A_o \sqrt{\frac{B}{A_o - B}} \sum_n \left(\sqrt{\frac{n+2}{n}} - 1 \right) \\ &\quad \times \, e^{i f_n t - \sqrt{\frac{B}{A_o - B}} \frac{f_{n+1} - f_n}{2} |t|}, \end{aligned} \tag{8}$$

where the simple expression for $\omega_n = \frac{c}{R_E}\sqrt{n(n+1)} = 2\pi f_n$ was used.

We now analyze the near stationary parametrization $\omega_n = \omega_n(t)$; it is an approximate solution of the Schumann resonances problem only if variations in ω_n happens in a time $t \gg 1/\omega_n$.

We can begin by $\omega_n(t) = \omega_n(h(t))$ expressing $h(t) = h_o + g(t)$ and $g(t) \ll h_o$, where h_o is the altitude of the ionosphere and $g(t)$ its perturbation, then if the Earth radius $R_E \gg h_o$

$$\omega_n(t) \simeq \frac{22\pi R_E \sqrt{n(n+1)}}{2R_E + h_o + g(t)}, \tag{9}$$

is the solution for crust and ionosphere considered as good conductors and where the numerical factor corrected it for the shift from the real case [127]. Simulations with many functions used for $g(t) \leq 10\% h_o$ (usually $h_o = 100Km$ then $g(t) \leq 10Km$ is also a high value) produced insignificant modifications in $\omega_n(t)$ and less again in $A(t)$. So we conclude that ionospheric altitude variations cannot understand anomalies in Schumann resonances when the model considers the perfectly conductive ionosphere.

Different models of ionosphere conductibility can be proposed to explain abnormal deviations of the Schumann resonances which suppose an exponential variation of the dielectric constant with respect to altitude [106]. To calculate the effect on the time evolution of the signal we should reconstruct it by a sum of several contributions of $A(t)$. We can imagine $A(t)$ as the impulsive contribution of lightning which occurred very faraway so that selectivity of the Earth-ionosphere cavity damped high frequency components and emphasized the Schumann spectrum. Then, the contribution of N lightning per second which strike randomly and gives a stochastic amplitude contribute can be modelled by

$$\mathcal{A}(t) = \sum_k \mathcal{R} A[t - (k + \mathcal{R}_k)/N], \tag{10}$$

where $\mathcal{R}$ and $\mathcal{R}_k$ are random numbers while index k stress the use of the same random number in the time expression of the exponent in (8). Figure 6 shows a simulation by pseudo-random functions of Mathematica, with $N = 30$, $n = 10$, $k = 400$ and $f_n = f_n(t) = 5.4(1 - 0.5\sin t)\sqrt{n(n+1)}$.

Appendix b)

To model the situation in figure 7 we should think of it as a system of conductors and dielectrics of simple geometry. The hole's source can be thought of as an expanding cloud of positive charge buried in a dielectric medium of constant ε_g and conductivity σ_g. The induced negative charge in the ionosphere can be thought in a conductive medium, with dielectric constant ε_i and conductivity σ_i which are constants in the height, which can produce a spherical bulge under the action of the force between the charges, see figure 9a).

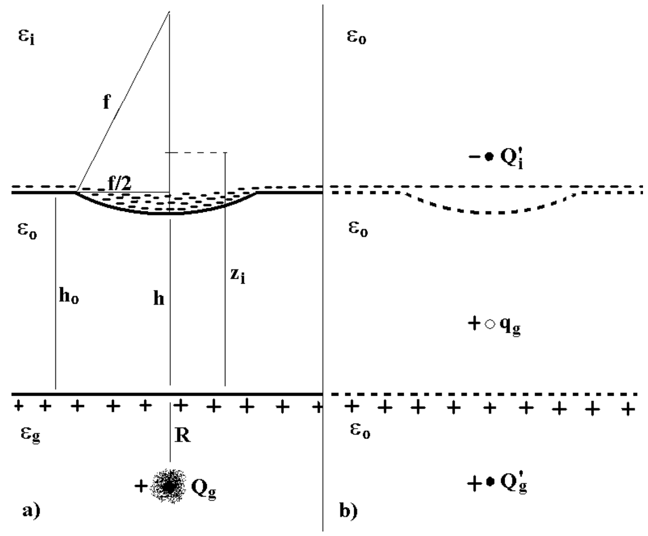

Figure 9: Model with the bulge under the ionospheric surface is showed in a); image charges are depicted in a vacuum space with ε_o in b).

Beginning by defining the source better we fix it in a spherical volume of radius R_o at the depth R of the hypocenter. We suppose that a current I_o of holes generates in it uniformly, so that a total charge $Q_g(t) = I_o t$ emerges in the volume with density $\rho_o(t) = \frac{3I_o t}{4\pi R_o^3}$. At this point the charge will tend towards the surface, but since the holes have a finite mobility, such a movement will happen with a delay. If we consider a point in the generation volume we can write the first Maxwell equation as

$$\vec{\nabla} \cdot \mathbf{J} = \frac{\sigma_g}{\varepsilon_g}\rho, \tag{11}$$

where $\mathbf{J} = \sigma_g \mathbf{E}$ was used and density $\rho = \rho_o + \rho_g$ was thought of as a contribution of the source and of the migration of the charges out of the source ρ_g. The density of current $\mathbf{J}$ produces an internal field $\mathbf{E}$ which can reach the surface with charges and we would then calculate it. Now, the continuity equation can be written as

$$\vec{\nabla} \cdot \mathbf{J} = -\frac{\partial \rho_g}{\partial t}, \tag{12}$$

being the term on the right different from zero because delays of the holes to restore equilibrium in a bad conductor like the ground. From the two equations we can define the dynamic of ρ_g by

$$\frac{\partial \rho_g}{\partial t} + \frac{\sigma_g}{\varepsilon_g}\rho_g + \frac{3\sigma_g I_o t}{4\pi\varepsilon_g R_o^3} = 0, \tag{13}$$

and solve it with simple methods to obtain the solution

$$\rho_g(t) = \frac{3I_o\tau_g}{4\pi R_o^3}\left(1 - \frac{t}{\tau_g} - e^{-t/\tau_g}\right), \tag{14}$$

where $\tau_g = \varepsilon_g/\sigma_g$. At this stage we can recover the density of current through the spherical surface of the source as

$$\mathbf{J}(R_o, t) = -\frac{R_o\hat{r}}{3}\frac{\partial \rho_g}{\partial t} = \frac{I_o\hat{r}}{4\pi R_o^2}\left(1 - e^{-t/\tau_g}\right). \tag{15}$$

Then the density of the current out of the source will be

$$\mathbf{J}(\mathbf{r}, t) = \frac{I_o\mathbf{r}}{4\pi r^3}\left(1 - e^{-t/\tau_g}\right). \tag{16}$$

Now we can write the expression of the electrical field immediately under the ground. To do this we suppose that activated holes do not concentrate themselves on the conductive earth surface but leave it and recombine. With the center of the source at distance R, which is the depth of the hypocenter, the ground field is

$$\mathbf{E}(R, t) = \frac{I_o\hat{r}}{4\pi\sigma_g R^2}\left(1 - e^{-t/\tau_g}\right). \tag{17}$$

This is the field that propagates at velocity $1/\sqrt{\mu_g\varepsilon_g}$ up to the surface. To simplify the ideas and calculus for the following we can think of the source as a punctual charge $Q_g(t)$ at depth R under the surface so that

$$\mathbf{E}(R, t) = \frac{Q_g(t)\hat{r}}{4\pi\varepsilon_g R^2}, \tag{18}$$

where $Q_g(t) = I_o\tau_g\left(1 - e^{-t/\tau_g}\right)$.

We will now discuss the effects of the variation of the dielectric and conductivity constants in the surface between crust and air on the electric field generated underground. First we can observe that the presence of a surface with dielectric differences will modify electric field in the crust itself because of attracting holes towards the surface. Then we can proceed through image charge methods to recover equivalent charges in order to calculate electric fields underground and over the surface. If we suppose the potential of the source to be generated by a charge $Q_g(t)$ concentrated in a spherical region with the center on the hypocenter within a sphere with radius $< r$ the electrical potential can be expressed by

$$V(r,t) = \frac{Q_g(t)}{4\pi\varepsilon_g r}. \tag{19}$$

The resolution of the problem consists in imagining a charge q_g symmetric with respect to the surface and another Q'_g at the same place of Q_g but in the vacuum. They are respectively used to calculate underground and over surface fields as in example [128]. By writing

$$\begin{aligned} V_1(p) &= \frac{Q_g}{4\pi\varepsilon_g r} + \frac{q_g}{4\pi\varepsilon_o r'}, \\ V_2(p) &= \frac{Q'_g}{4\pi\varepsilon_o r}, \end{aligned} \tag{20}$$

where r' is the distance the image charge from the point p, the boundary conditions $V_1 = V_2$ and $\varepsilon_g \partial_n V_1 = \varepsilon_o \partial_n V_2$ produce

$$\begin{aligned} q_g &= Q_g \frac{\varepsilon_g - \varepsilon_o}{\varepsilon_g + \varepsilon_o}, \\ Q'_g &= Q_g \frac{2\varepsilon_o}{\varepsilon_g + \varepsilon_o}, \end{aligned} \tag{21}$$

while the force between total charges Q_g and q_g can be evaluated [128] by

$$F = \frac{Q_g^2}{4\varepsilon_g R^2} \frac{\varepsilon_g - \varepsilon_o}{\varepsilon_g + \varepsilon_o} > 0 \tag{22}$$

being the force rejecting the holes inward. Finally we can obtain ground and external field in Cartesian coordinates as

$$\begin{aligned} \mathbf{E}_g(\mathbf{r}_o) &= \frac{Q_g[(x-x_o)\hat{\imath} + y\hat{\jmath} + (-R-z_o)\hat{k}]}{4\pi\varepsilon_o\varepsilon_g r_Q^{3/2}} \\ &\quad + \frac{q_g[(x-x_o)\hat{\imath} + y\hat{\jmath} + (R-z_o)\hat{k}]}{4\pi\varepsilon_o\varepsilon_g r_q^{3/2}}, \\ \mathbf{E}_e(\mathbf{r}_o) &= \frac{Q'_g[(x-x_o)\hat{\imath} + y\hat{\jmath} + (-R-z_o)\hat{k}]}{4\pi\varepsilon_o r_{Q'}^{3/2}}, \end{aligned} \tag{23}$$

where $\mathbf{r}_o$ is the vector of the measurement point, z_o is negative for $\mathbf{E}_g$ and positive for $\mathbf{E}_e$. $\mathbf{r}_Q$, $\mathbf{r}_q$ and $\mathbf{r}_{Q'}$ are the vectors between $(x_o, 0, z_o)$ and the respective charge positions.

Now we can see the ionospheric contribution to the electric field. The ionosphere can be thought of as a layer composed by free electrons where dielectric constant and conductivity ε_i and σ_i are constants for $z > h_o$. Supposing that a deformation of the layer appears under it because of the generation of holes in the ground. This deformation can be imagined as a spherical bulge, see figure 9a). We still make use of image charges to simplify the model and impose that such charge is induced in the ionosphere from those in the ground to obtain an equipotential spherical surface in the volume of the ionosphere lacking electrons, see figure 9b). Such a spherical surface can be thought of as if a slice of sphere was under the ionospheric boundary at h_o, so that the horizontal radius of the bulge is $\frac{1}{2}f(M,R)$ and the radius of the sphere is $f(M,R)$, where M is the magnitude of the event, R its depth and the function could be of the type $f(M,R) = \alpha R^{-\beta} e^{\gamma M}$. Above the hypocenter the height of the ionosphere will be $h = h_o - 0.134 f(M,R)$. Supposing that the free charges in the ionosphere do not modify charge distribution in the ground, we calculate image charge Q'_i in a vacuum ionosphere so that the potential on the sphere is zero. With common methods it is possible to obtain

$$Q'_i = -Q'_g \frac{R}{R + h + f(M,R)} \tag{24}$$

and its height z_i will be

$$z_i = h + f(M,R) - \frac{R^2}{R + h + f(M,R)}, \tag{25}$$

so that

$$\mathbf{E}_i(\mathbf{r}_o) = \frac{Q'_i[(x-x_o)\hat{\imath} + y\hat{\jmath} + (z_i - z_o)\hat{k}]}{4\pi\varepsilon_o r_i^{3/2}}, \tag{26}$$

where $\mathbf{r}_i$ is the vector between $(x_o, 0, z_o)$ and the charge Q'_i. The total field, see figure 9b), can be now obtained as the simple sum

$$\mathbf{E}(\mathbf{r}_o, t) = E_o\hat{k} + \mathbf{E}_e(\mathbf{r}_o, t) + \mathbf{E}_i(\mathbf{r}_o, t), \tag{27}$$

where E_o is the constant field between Earth and the ionosphere.

Appendix c)

In a situation where a pair of electrodes are buried underground we suppose them equivalent to the system in which two plates select a precise channel of conduction in the crust, see figure 7 I). In this situation an electric field is induced from a variable magnetic field between the electrodes. A general relation that defines such a process in a medium with conductivity σ_g in the presence of an oscillating magnetic field $\vec{B}(t) = B_o\hat{y}\sin(\omega t)$ can be written as [65]

$$E(t)\hat{x} = -B_o\hat{y}\sqrt{\frac{\omega}{2\sigma_g\mu_g}}\sin(\omega t + \pi/4). \tag{28}$$

If the distance between the electrodes is $\ll R$, so that the front of positive carriers can be considered flat, it is possible to define a medium conductivity

$\bar{\sigma}_h$ in the conductive channel partially invaded by the holes as

$$\frac{1}{\bar{\sigma}_h(t)} = \frac{1}{\sigma_h} - \frac{R-r(t)}{D}\left(\frac{1}{\sigma_h} - \frac{1}{\sigma_g}\right), \qquad (29)$$

where $r(t)$ is the position of the front of the holes, D is the square dimension of the electrodes and σ_h is the conductivity acquired by holes.

In a complementary way telluric electric fields can manifest themselves as currents which produce magnetic fields. We suppose $E_x\hat{i}$ to be a constant telluric field which characterizes the conductive crust of figure 7 I), considering the conductive channel a sum of an infinity of thin wire each generating an infinitesimal magnetic induction above surface

$$d\mathbf{B}(\mathbf{r}) = \frac{\mu_o \hat{x}\times\hat{r}}{4\pi r}dI, \qquad (30)$$

imply that

$$B = \frac{\mu_o}{4\pi}\int_0^D dz \int_{-D/2}^{D/2} \frac{J(z)}{\sqrt{y^2+z^2}}\cos\theta dy, \qquad (31)$$

where $\cos\theta = z/\sqrt{y^2+z^2}$ and $J(z) = \sigma_g E_x$ for $-R+r(t) \le z \le 0$ while $J(z) = \sigma_h E_x$ for $z \le -R+r(t)$. The integrals can be solved first in z and after in y by changing variables and by parts. After some work we obtain

$$B(z_o,t) = \frac{\mu_o E_x}{8\pi}\left\{\frac{\sigma_h}{D+z_o}G\left(\frac{D+z_o}{D}\right) - \frac{\sigma_g}{z_o}G\left(\frac{z_o}{D}\right) - \frac{\sigma_h-\sigma_g}{R+z_o-r(t)}G\left[\frac{R+z_o-r(t)}{D}\right]\right\}, \qquad (32)$$

where

$$G(x) = 4\arctan(2x) - \frac{1}{x}\ln(1+4x^2). \qquad (33)$$

References

[1] C. Fidani, *Ipotesi sulle Anomalie Elettromagnetiche Associate ai Terremoti*, Libreria Universitaria Benedetti Ed., L'Aquila, Luglio 2005, pp.5-11;

[2] M. A. Persinger, *Possible Infrequent Geophysical Source of Close UFO Encounters: Expected Physical and Behavioral-Biological Effects*, Chapter 13 of *UFO Phenomena and Behavioral Scientist*, Scarecrow Press 1979 in Heines R. F. Ed., p.400;

[3] ib. C. Fidani, pp.17-38;

[4] E. P. Strand, Project Hessdalen 1984: Final Technical Report, 1984, http://hessdalen.hiof.no/reports/hpreport84.shtml;

[5] M. Teodorani et al., EMBLA 2001: The Optical Mission, ICPH Report 2001;

[6] S. K. Park, Precursors to Earthquakes: Seismo Electromagnetic Signals, Survey in Geophysics, Vol.17, p.493, 1996;

[7] M. J. S. Johnston, Review of Electricc and Magnetic Fields Accompanying Seismic and Volcanic Activity, Survey in Geophysics, Vol.18, p.441, 1997;

[8] P. Varotsos, A Review and Analysis of Electromagnetic Precursory Phenomena, Acta Geophysica Polonica, Vol.XLIX, n.1, p.1, 2001;

[9] M. Teodorani and E. P. Strand, Data Analisys of Anomalous Luminous Phenomena in Hessdalen, Eurp. J. of UFO and Abduc. Stud., Vol.1, n.2, p.64, 2000;

[10] A. Junge, Characterization of and Correction for Cultural Noise, Survey in Geophysics, Vol.17, p.361, 1996;

[11] A. Tzanis and S. Gruszow, On the Problem of Identification and Discrimination of Electrical Earthquake Precursors, Phys. Chem. Earth, Vol. 23, n.9-10, p.939, 1998;

[12] V.-N. Pham et al., Electromagnetic Signals Generated in the Solid Earth by Digital Transmission of Radio-Waves as a Plausible Source for some so-called 'Seismic Electric Signals', Phys. Earth and Plan. Int., Vol.114, p.141, 1999;

[13] R. Barr et al., ELF and VLF radio waves, J. of Atm. and Solar-Terrestrial Phys., Vol.62, p.1689, 2000;

[14] M. Hayakawa et al., Natural Electromagnetic Phenomena and Electromagnetic Theory: A Review, IEEJ Trans. FM, Vol.124, n.1, 2004;

[15] G. Vannucci, Discorso Istorico Filosofico sopra il tremuoto del 25 dicembre 1786, Cesena, 1787;

[16] A. Maccioni, Nuova scoperta nel campo della sismologia, Atti della R. Accademia dei Fisiocritici in Siena, Vol.1, p.435-444, 1909;

[17] Y. Zhao and F. Quian, Geoelectric precursorsto strong earthquakes in China, Tectonophysics, Vol.233, p.99, 1994;

[18] I. Kant, *Scritti sul Terremoto*, Edizioni 10/17, 1984;

[19] G. Ferrari, The 1887 Ligurian earthquake: a detailed study from contemporary scientific observations, Tectonophysics, Vol.193, p.131-139, 1991;

[20] S. Breiner, Piezomagnetic effect at the time of local earthquakes, Nature, Vol.202, p.790, 23 May 1964;

[21] G. W. Moore, Magnetic disturbances preceding the 1964 Alaska earthquakes, Nature, Vol.203, p.508, 1 August 1964;

[22] G. Alfani, Il terremoto sarà preveduto? Lo strumento di Padre Maccioni, Corriere della Sera, 9 maggio 1909;

[23] P. Kapiris, VHF-electromagnetic evidence of the underlying pre-seismic critical stage, Earth Planets Space, Vol.54, p.12371246, 2002;

[24] A. A. Tronin, Thermal IR satellite sensor data application for earthquake research in China, International Journal of Remote Sensing, Vol.21, n.16, pp.3169-3177, 2000;

[25] S. Yu. Aleksandrin et al., High-energycharged particle bursts in the near-Earth space as earthquake precursors, Ann. Geophysicae, Vol.21, p.597-602, 2003;

[26] W. Hamilton, An Account of the Late Eruption of Mount Vesuvius. In a Letter from the Right Honourable Sir William Hamilton, K.B.F.R.S. to Sir Joseph Banks, Bart. P.R.S., Phylosophical Transactions of the Royal Society of London, Vol.85, pp.75-116, 1795;

[27] J. Zlotnicki el al., Ground-based electromagnetic studies combined with remote sensing based on Demeter mission: A way to monitor active faults and volcanoes, Planetary an Space Science, Vol.54, pp.541-557, 2006;

[28] V. Sgrigna et al., Correletions between earthquakes and anomalous particle burst from SAMPLEX/PET satellite observations, J. Atm. Solar-Terrestrial Phys., Vol.67, pp.1448-1462, 2005;

[29] ib. C. Fidani, pp.1-5;

[30] I. Galli, Raccolta e classificazione dei fenomeni luminosi osservati nei terremoti, Boll. della Soc. Italiana, Vol.14, pp.221-448, 1910;

[31] J. S. Derr, Earthquake lights: a review of observations and present theories, Bull. Seis. Soc. Am., Vol.63, n.6, p.2177, 1973;

[32] Debate on "VAN", Geophysical Research Letters, Vol.23, pp.1291-1452, 1996;

[33] M. Baratta, *I Terremoti D'Italia*, ARNALDO FORNI EDITORE, Ristampa anastatica dell-edizione di Torino, da p. 154, 1901;

[34] G. Martinelli, Non seismometrical precursors observations in Europe: steps of earthquake prediction research, Historical Seismic Instruments and Documents: a Heritage of Great Scientific and Cultural Value Proc. Workshop, pp.195-216, 1997;

[35] M. Caputo, *Sismologia e segnali precursori dei terremoti*, Calderini, Bologna, pp.103-104, 1987;

[36] F. M. Grimaldi, *Physico-mathesis de Lumine, Coloribus et Iride aliisque adnexi libri duo*, Bologna, pp.470, 1665;

[37] W. Stukeley, On the causes of Earthquakes, Phil. Transact., Vol.XLVI, n.491, pp.641-646, 1750;

[38] A. Bina, *Ragionamento sopra la cagione de terremoti*, Perugia, 1751;

[39] Rozier, Journal do Physique, Aout, 1779;

[40] E. Giudoboni and G. Ferrari, *Il terremoto di Rimini e della costa romagnola: 25 dicembre 1786 Analisi e interpretazione*, SGA, Bologna, 1996;

[41] G. Vannucci, *Discorso Istorico Filosofico sopra il tremuoto del 25 dicembre 1786*, Cesena, 1787;

[42] G. Vivenzio, *Istoria dé tremuoti avvenuti nella provincia di Calabria Ulteriore, e nella città di Messina nell'anno 1783e di quanto nelle Calabrie fu fatto per il suo risorgimento fino al 1787. Preceduta da una ulteriore teoria, ed istoria generale dé tremuoti*, Napoli, 1788;

[43] M. Moreschini, *Ragionamento storico-filosofico sul tremuoto di Camerino il dí 28 luglio 1799*, Camerino, 1802;

[44] A. Volta, *Memoria. Sopra i Fuochi de' Terreni e delle Fontane ardenti in generale, e sopra quelli di Pietra-Mala in particolare*, in Memorie di matematica e di fisica della Societ Italiana, tomo II, parte II, per Dionigi Ramazzini, Verona, pp.662-665, 1784;

[45] M. Caputo, Introduzione al Convegno, in Terremoti in Italia. Atti dei Convegni Lincei, Accademia Nazionale dei Lincei, Roma, pp.3-5, 1995;

[46] A. Serpieri, Sullo studio della perturbazione elettrica foriera del terremoto, *Scritti di Sismologia*, Urbino, Vol.I, pp.206-217, 1874;

[47] A. Serpieri, L'avvenire della sismologia e la predizione dei terremoti, in Rivista Scientifica, Siena, aprile 1878;

[48] Raffaele Bendandi a Firenze, Il sismologo faentino a colloquio con Padre Alfani e Padre Stiattesi, La Nazione, 1 febbraio 1924;

[49] U. Mondello, Sulla presenza di onde elettromagnetiche precorritrici del sismo, Pubblicazioni dell'osservatorio di Ardenza di Mare 4, Livorno, 1909;

[50] A. Maccioni, Nuova scoperta nel campo della sismologia, Atti della R. Accademia dei Fisiocritici in Siena, Vol.1, pp.435-444, 1909;

[51] T. Calzecchi-Onesti, Di una nuova forma che può darsi all'avvisatore microsismico, Nuovo Cimento, serie 3, XIX, pp.24-26, 1886;

[52] G. Ceramicola, Di un nuovo avvisatore sismico, La scienza per tutti, 1 marzo 1911;

[53] E. Ungania, *Presismofono Ungania. Unico apparecchio preavvisatore dei terremoti, segnalatore delle perturbazioni elettromagnetiche*, Bologna, 1924;

[54] TROMOS project devoted to researching, recovering, restoring and re-establishing of the historical heritage of scientific earthquake observation in Italy, developed by SGA Storia Geofisica Ambiente of Bologna, Italy, http://storing.ingv.it/tromos/comments/COMM01042.htm

[55] U. Marchetti, Padre Alfani constata l'esattezza delle previsioni del falegname sismologo mentre il prof. Malladra esclude la possibilità di prevedere i terremoti, Corriere Italiano, 1 febbraio 1924;

[56] D. Bohm, *Causality and change in modern physics*, Routledge, London, p.97, Reprinted 1997;

[57] G. Ferrari, edited by, *Two hundred years of seismic instruments in Italy 1731-1940*, ING-SGA Bologna 1992.

[58] R. Stoneley, *History of modern seismology*, In: International dictionary of geophysics, edited by Stanley Keith Runcorn et al., Pergamon Press Oxford, Oxford, 1967;

[59] ib. E. Ungania, p.14;

[60] A. Comte, *A Discourse on the Positive Spirit*, Reeves, London 1903;

[61] ib. E. Ungania, p.6;

[62] R. Bendandi, *Le stelle soli dell'infinito*, ed. by Cristiano Fidani, EDIT Faenza, p.4, Faenza maggio 2006;

[63] ib. R. Bendandi, pp.6-26;

[64] ib. R. Bendandi, p.9;

[65] E.M. Lifstis and L.P. Pitaevskij, *Elettrodinamica dei mezzi continui*, MIR, Mosca, p.299, 1986;

[66] E. Hauksson, Radon content of groundwather as an earthquake precursor: evaluation of worldwide data and physical basis, J. Geophys. Res., Vol.86, p1981;

[67] A.M. Galper, et al., Interrelation between high-energy charged particle fluxes in the radiation belt seismicity of the Earth, Cosmic Res., Vol.27, p.789, 1989;

[68] N. Wadsworth, The Amateur Scientist, column in Scientific American, February, 1968;

[69] H.C. Séran and P. Fergeau, An optimized low-frequency three-axis search coil magnetometer for space research, Rev. Sci. Instrum. 76, 044502, 2005;

[70] D. Drung et al., Low-noise high-speed dc superconducting quantum interference device magnetometer with simplified feedback electronics, Appl. Phys. Lett., Vol.57, n.4, pp.506-508, 1990;

[71] P. Varotsos and K. Alexopoulos, Physical properties of the variations of the electric field of the Earth preceedng earthquakes, I, Thectonophysics, Vol.110, pp.73-98, 1984;

[72] H. Sasaki et al., ELF electromagnetic wave observation system on seabed, in Electromagnetic phenomena related to earthquake prediction, Terrapub, Tokyo, pp.193-204, 1994

[73] M. Parrot, The micro-satellite Demeter, J. Geodyn., Vol.33, pp.535541, 2002;

[74] P.F. Biagi el al., Variations in LF radio signal on the occasion of the recent seismic and volcanic activity in Southern Italy, Phys. Chem. Earth, Vol.29, p.551, 2004;

[75] A. Peacock, et al., Single optical photon detection with a superconducting tunnel junction, Nature, Vol.381, pp.135-137, 1996;

[76] E.A. Gerken, Telescopic imaging of streamer and diffuse glow dynamics in sprites, Degree of Doctor of Philosophy, Standford University, July 2003;

[77] S.B. Utter, et al., Design and implementation of a high-resolution, high-efficiency optical spectrometer, Rev. Sci. Inst., Vol.73, n.11, p.3737, 2002;

[78] S. Komiyama, et al., A single-photon detector in the far-infrared range, Nature, Vol.403, n.6768, pp.405-7, 2000;

[79] S. Breiner, Piezomagnetic effect at the time of local earthquakes, Nature, Vol.202, p.790, 23 May 1964;

[80] G.W. Moore, Magnetic disturbances preceding the 1964 Alaska earthquakes, Nature, Vol.203, p.508, 1 August 1964;

[81] A.J. Mannucci, et al., Dayside global ionospheric response to the major interplanetary events of October 2930, 2003 "Halloween Storms", Geophys. Res. Lett., Vol.32, L12S02, 2005;

[82] V. Gennaro and D. Giaiotti, Misure del campo elettrico terrestre nella valle di Hessdalen, ICPH Report, 2004;

[83] H. Murakami, et al., Self-potential anomalies associated with an active fault, J. Geomag. Geoelectr., Vol.36, pp.351-376, 1984;

[84] Y.F. Contoyiannis, P.G. Kapiris and K.A. Eftaxias, Monitoring of a preseismic phase from its electromagnetic precursors, Phys. Rev. E, Vol.71, 066123, 2005;

[85] M. Parrot, et al., High-frequency seismo-electromagnetic effects, Phys. Earth Plan. Int., Vol.77, pp.65-83, 1993;

[86] M.J.S. Johnston, Review of magnetic and electric field effects near active faults and volcanoes in the U.S.A., Phys. Earth Plan. Int., Vol.57, pp.47-63, 1989;

[87] ib. C. Fidani, pp.137-269;

[88] A. Sornette and D. Sornette, Electromagnetic rupture as a critical point: consequences for telluric precursors, Tectonophysics, Vol.179, p.327, 1990;

[89] D. Finkelstein et al., The piezoelectric theory of earthquake lightning, J. Geophys. Res., Vol.72, n.6, p.992, 1973;

[90] N. Nakamura and H. Nagahama, Geomagnetic field perturbation and fault creep motion: a new tectonomagnetic model, TERRAPUB, Tokyo, Ed. by M. Hayakawa, in: Atmospheric and ionospheric electromagnetic phenomena associated with earthquakes, p.307, 1999;

[91] Y. Sasai, Tectonomagnetic modelling on the bases of the linear piezomagnetic effect, Bull. Earthq. Res. Inst. Univ. Tokyo, Vol.66, p.585, 1991;

[92] H. Mizutani, T. Ishido, T. Yokokura and S. Ohnishi, Electrokinetic phenomena associated with earthquakes, Geophys. Res. Lett., Vol.3, n.7, p.365, 1976;

[93] M.A. Fenoglio et al., Magnetic and electric fields associated with changes in high pore pressure in fault zone: applications to the Loma Prieta ULF emissions;

[94] ib. C. Fidani, pp.40-136;

[95] P. Bernard, Plausibility of long distance electrotelluric precursors to earthquakes, J. Geophys. Res., Vol.97, n.B12, p.17531, 1992;

[96] P. Varotsos, N. Sarlis, M. Lazaridou and P. Kapiris, Transmission of stress induced electric signals in dielectric media, J. Appl. Phys. Vol.83, n.1, p.60, 1998;

[97] E.R. Mognaschi, Precursori elettromagnetici dei sismi, RADIOONDE, n.12, maggio 1998, http://www.anisn.it/geologia2000/index.html;

[98] E.R. Mognaschi, On the possible origin, propagation and detectability of electromagnetic precursors of earthquakes, Atti Ticinensi di Scienze della Terra, vol.43, pag.111-118, 2002, http://www.vlf.it/;

[99] A. Nardi and M. Caputo, A perspective electric earthquake precursor observed in the Apennines, Bollettino di Geofisica Teorica ed Applicata, Vol.47, n.1-2, pp.3-12; March-June 2006;

[100] Y. Zhao and F. Quian, Geoelectric precursors to strong earthquakes in China, Tectonophysics, Vol.233, p.99, 1994;

[101] F. Quian, Y. Zhao and R. Teisseyre, Periodic anomalies of the telluric electric field before the Thangshan earthquake and a model of electrikinetic precursors triggered by tidal forces, Acta Geiphys. Pol., Vol.38, n.3, p.245, 1990;

[102] M.N. Fatkullin, T.I. Zelenova and A.D. Legenka, On the ionospheric effects of asthenospheric earthquakes, Phys. Earth Plan. Int., Vol.57, p.76, 1989;

[103] ib. C. Fidani, pp.266-269;

[104] W.O. Schumann, *Ü*ber die strahlungslosen Eigenschwingungen einer leitenden Kugel, die von einer Luftschicht und einer Ionosph*ä*renhu h*ü*lle umgeben ist, Z. Naturforsch. A, Vol.7, pp.149154, 1952.

[105] K. Ohta, N. Watanabe and M. Hayakawa, Survey of anomalous Schumann resonance phenomena observed in Japan, in possible association with earthquakes in Taiwan, Phys. Chem. Earth, Vol.31, pp.397402, 2006;

[106] V.C. Roldugin, Y.P. Maltsev, A.N. Vasiljev, A.V. Shvets and A.P. Nikolaenko, Changes of Schumann resonance parameters during the solar proton event of July 14, 2000, J. Geophys. Res., Vol.108, n.A3, p.1103, 2003;

[107] K. Schlegel and M. F*ü*llekrug, Schumann resonance parameters changes during high-energy particle precipitation, J. Geophys. Res., Vol.104, n.A5, pp.10,111-10,118, 1999;

[108] H.J. Christian et al., Global frequency and distribution of lightning as observed from space by the Optical Transient Detector, J. Geophys. Res., Vol.108, n.D1, p.4005, 2003;

[109] J.D. Jackson, *Classical Electrodynamics*, 2^a ed., Wiley, New York, 1975;

[110] L.D. Landau and E.M. Lifshitz, *Mechanics*, Pergamon, Oxford, 1969;

[111] A. Lambrecht, M.-T. Jaekel, and S. Reynaud, Motion induced radiation from a vibrating cavity, Phys. Rev. Lett., Vol.77, n.4, 1996;

[112] J.-Y. Ji, K.-S. Soh, R.-G. Cai and S.P. Kim, Electromagnetic fields in a three-dimensional cavity and in a waveguide with oscillating walls, J. Phys. A, L457-L462, 1998;

[113] D.D. Sentman and B.J. Fraser, Simultaneous observations of Schumann resonances in California and Australia: evidence for intensity modulation by the local eight of the D region, J. Geophys. Res., Vol.96, n.A9, p.15973, 1991;

[114] F.T. Freund, Time-resolved study of charge generation and propagation in igneous rocks, J. Geophys. Res., Vol.105, n.B5, p.11001, 2000;

[115] F.T. Freund, Charge generation and propagation in igneous rocks, J. Geodyn., Vol.33, pp.543-570, 2002;

[116] F.T. Freund, A. Takeuchi and Bobby W.S. Lau, Electric currents streaming out of stressed igneous rocks A step towards understanding pre-earthquake low frequency EM emissions, Phys. Chem. Earth, Vol.31, pp.389396, 2006;

[117] V.M. Sorokin, et al., Electrodynamic modelling of the lower atmospher and the ionosphere coupling, J. Atm. Solar-Terr. Phys., Vol.63, pp.1681-1691, 2001;

[118] V.M. Sorokin, et al., DC electric field amplification in the mid-latitude ionosphere over seismically active faults, Phys. Chem. Earth, Vol.31, pp.447-453, 2006;

[119] B.T. Tsurutani, et al., The October 28, 2003 extreme EUV solar flare and resultant extreme ionospheric effects: Comparison to other Halloween events and the Bastille Day event, Geophys. Rev. Lett., Vol.32, L03S09, 2005;

[120] M.D. Looper and J. B. Blake, Response of the inner radiation belt to the violent Sun-Earth connection events of OctoberNovember 2003, Geophys. Rev. Lett., Vol.32, L03S06, 2005;

[121] K. Meyer and R. Teisseyre, Electrotelluric periodic anomalies prior to large imminent earthquakes, Acta Geophys. Pol., Vol.36, n.4, p.309, 1988;

[122] D. Bohm and F.D. Peat, *Science, Order and Creativity*, 2nd ed., Routledge, 2000;

[123] F.T. Freund, Rocks that crackle and sparkle and glow: strange pre-earthquake phenomena, J. Sci. Explor., Vol.17, n.1, pp.37-71, 2003;

[124] ib. C. Fidani, pp.40-98;

[125] V. Dikhtyar and E. Jerby, Fireball Ejection from a Molten Hot Spot to Air by Localized Microwaves, Phys. Rev. Lett., Vol.96, 045002, 2006;

[126] A. Swarup, Physicists create great balls of fire, New Scientist, 07 June 2006;

[127] R.W. Row, On the electromagnetic resonant frequencies of the Earth ionosphere cavity, IRE Trans. Ant. Prop., pp.766-769, November 1962;

[128] E.M. Lifsits and L.P. Pitaevskij, *Elettrodinamica dei mezzi continui*, MIR. Mosca, p.63, 1986.