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Review

Progress in the Knowledge, Application and Influence of Extremely Low Frequency Signals

Rosa M. García, Nuria Novas *, Alfredo Alcayde, Dalia El Khaled, Manuel Fernández-Ros and José Antonio Gazquez

Department of Engineering, CeiA3, University of Almeria, 04120 Almeria, Spain; rgarciasalvador@ual.es (R.M.G.); aalcayde@ual.es (A.A.); dalia.elkhaled@gmail.com (D.E.K.); mfernandez@ual.es (M.F.-R.); jgazquez@ual.es (J.A.G.)

* Correspondence: nnovas@ual.es

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Featured Application: Carrying out the state-of-the-art study of the different applications of extremely low frequency (ELF) waves has enabled the determination of the importance of these signals in different fields. They are of special interest for the knowledge of natural phenomena, the development of communications, and in various medical applications. The great diversity of existing applications is reflected in the numerous investigations developed over the years. At present, ELF waves are still considered to be a subject of special interest due to their great potential, a fact that has been highlighted in this paper.

Abstract: This paper describes the characteristics of contributions made by researchers worldwide in the field of ELF (extremely low frequency) waves from 1957 to 2019. The data were collected through the Scopus database and processed with analytical and bibliometric techniques. The selection of the keywords is an essential step, because ELF has a very different meaning in some areas of medicine, where it is associated with a gene. A total of 12,436 documents were worked on in 12 thematic communities according to their collaborative relationships between authors and documents. Studies included authors publishing in the different thematic areas and the country where the USA stands first with more researchers in this theme than China and Japan. Documents were analyzed from the temporal perspective, their overall contribution, means of publication, and the language of the publication. Research requires extra effort and multidisciplinary collaboration to improve the knowledge, the application, and influence of these fields.

Keywords: extremely low frequency; Scopus; electromagnetic field; cancer; occupational exposure; exposure assessment; lightning ELF phenomena

1. Introduction

The exposure to electromagnetic fields of natural or artificial origin is common in our society, where continuous technological developments increase the knowledge and evolution of these fields. Among the existing signals, the study and determination of extremely low frequency (ELF) signals, located in the range of 0.3 Hz to 0.3 kHz, is increasingly important and demanded, and scientific contributions based on this topic date from 1957 to the present. Although all the investigations carried out on ELF signals have a common basis such as the generation-reception of waves, they cover different areas of application. For an antenna to generate or receive a very-low-frequency wave, it requires dimensions of the order of the wavelength it is radiating so this process is not trivial. ELF signals have wavelengths of the order of the Earth's diameter, so to transmit these signals, the Earth itself should be used as an antenna [1]. The need to establish large antennas, together with the wide applications of

this type of signal in ionospheric systems, magnetospheric systems, remote sensing, and long-distance communications, among others, implies the multidisciplinary development of scientists based on the establishment of efficient ELF signal radiation [2]. Different mechanisms are considered to generate these signals [3], among which the high frequency modulated ionospheric heating (HF) predominates bibliographically [4].

The determination of ELF signals derived from natural electromagnetic phenomena is a topic of special interest, since it involves multidisciplinary branches among which geophysics, astrophysics, engineering, climatology, earth sciences, etc. are distinguished. The most relevant ELF electromagnetic waves in the planet's tropospheric-ionospheric system include Schumann resonance (SR), geomagnetic pulsations, and waves related to the Alfvén resonator mode [5]. SR are the resonance modes that exist in the cavity established between the Earth's surface and the lower edge of the ionosphere [6]. These signals were initially observed in the 1960s [7] and remain a topic of study today [8]. The geomagnetic pulses are hydro-magnetic waves that arise from resonant processes and propagate in the magnetosphere [9]. They are a valuable tool for investigating the connections between the Sun and the Earth, the interaction between the solar wind and the magnetosphere, the dynamics of the magnetosphere, and the auroral processes [10]. On the other hand, Alfvén waves are oscillations that occur in an ionized fluid permeated by a magnetic field, such as the Earth's ionosphere or the magnetosphere [11,12]. They play an important role for the knowledge of the Sun, the interstellar medium and the Earth's magnetosphere [13,14]. Observations of natural ELF radiation have formed the cornerstone in the measurement and interpretation of the effects of lightning in the upper atmospheric regions, as well as in the space near the Earth [15], where the most used tool is the signals derived from SR. SR has been used to investigate the electrical processes that occur in the atmosphere [16], the characteristics of the surface and the lower ionosphere, as well as the tropospheric-ionospheric coupling [5] applied to the Earth and Mars [17], to Saturn [18], or Venus [19], among other celestial bodies. These signals have also been studied as precursor elements of seismic events, due to the variability of SR records in the presence of earthquakes [20], being a topic widely researched in recent decades [21]. The diverse applicability of these signals, together with the complexity of their detection [22] and the need to develop specific equipment for the measurements [23], have been widely developed research topics in recent years and even today they are considered topics of interest as they are not efficiently resolved [24].

Magnetospheric ELF emissions are also important and have aroused great scientific interest since 1969 [25]. There are several types of emissions that depend on the presence of rays in regions of high density plasma or plasma spherical whistles among which some are the subject of frequent study in the literature [26]. These emissions allow knowledge of the structure and dynamics of the radiation belts. Another type is choir emissions or magnetospheric choir emissions. These emissions are due to the anisotropic distribution of energy electrons within the magnetosphere [27], and it has been proven that they provide information on the region of the magnetosphere where they occur and the mechanism that generated it.

Exposure to natural and especially artificial ELF electromagnetic fields (ELF-EMF), emanating from the generation, transmission, and use of electricity, is a ubiquitous part of modern life [28]. Establishing the influence of these fields has become a necessity and a topic widely studied in recent decades where most of the publications on this subject are concentrated. In 1970 the first study that tried to determine the effects of this type of field on animals, laboratory rats specifically, was published [29]. All studies carried out from that moment to the present have had and pursue the same objective: trying to determine if we are safe from the adverse effects of ELF-EMF, in order to achieve a better quality of life for current populations, as well as future populations. Different genetic changes such as cell and membrane modification, tissue damage, changes in protein conformation, modification in the absorption of different biological components, and modifications in genetic material, have been considered as possible biological effects of ELF radiation, etc. [30]. A topic of special interest is the relationship between exposure to ELF fields and the risk of development of cancer cells or carcinogenesis, as a relationship is found between said exposure and the reduction of melatonin that is

involved with the possible development of cancers [31]. Research was also carried out to determine the effects of these ELF fields on the cardiovascular system [32], considering the cardiac constants by electrocardiograms (ECG). As well as the influence of the fields on the nervous system for different functional changes [33], or on the functional state of the brain by carrying out the measurement of brain activity by electroencephalogram (EEG) of different test subjects, whether animals or people [34]. The final objective of all these studies was aimed at being able to use the effects of these fields on different brain functions in order to produce controlled modulation of regional activity and become a very useful non-invasive tool for the treatment of neurological and neuropsychiatric disorders. Despite the large number of studies carried out, the relationship of the effects of exposure to ELF fields has not yielded conclusive data, most have problems related to the existence of interference, or the inability to accurately reproduce the conditions of some studies compared to others. Therefore, this issue is unresolved and needs further advanced research [35].

Currently, research on ELF waves continues in different fields from engineering, astrophysics, medicine, and even biology [36], as indicated by the large number of scientific contributions found in these areas. These contributions have doubled per decade, which implies a huge number of documents distributed within the same field of research by scientific communities. The collaboration of the authors in different thematic communities makes the progress of science more productive, since there are not only research relationships between authors but also between institutions. Science and technology are in continuous development through these collaborations, so it is necessary to establish metrics to determine the relationships between the authors. This has been taken care of in this document where the different communities that have been established over time have been consolidated in the investigation of ELF waves and the main contributions from each of them and their relationships are analyzed.

2. Materials and Methods

This paper studies all world scientific publications whose topic is ELF waves (0.3–300 Hz), indexed in the Scopus database. On the web, there are several search engines that are based on scientometric indicators such as the number and the quality of the contributions according to the metric of the magazine or the author. However, the results of these searches do not measure the relationships between the authors and the different collaboration communities that can be established [37]. From among the existing databases, Scopus has been selected, since it is the scientific database with the greatest contributions in publications worldwide [38].

For the automatic obtaining of bibliographic data from the scientific publications of Scopus, an API (Application Programming Interface) rasNetBot interface is used, developed by the research group of the engineering department of the University of Almeria (Spain) [39]. The extraction process can be divided into several stages:

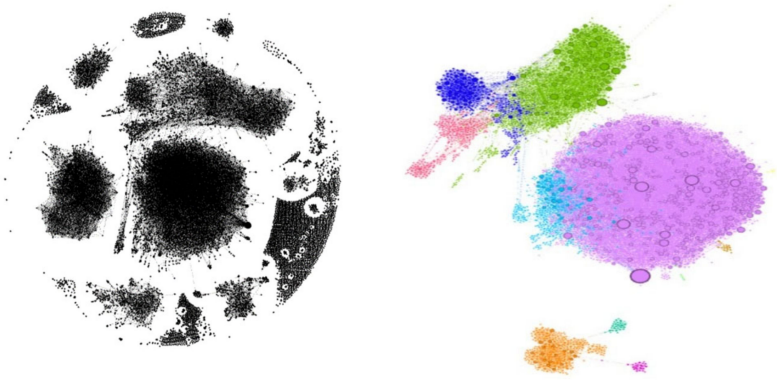
(1) Obtaining information about documents that contain the established keywords initially contained in the summary, title, or keywords fields of the document.
(2) Extracting the information of the authors of the works mentioned in step (1), including for each author the Scopus identification number of the author, affiliations, publications, dates, number of citations, and H-index.
(3) Processing to obtain the collaborative network of authors who have published articles that contain the search keywords.

For our search, TITLE-ABS-KEY “ELF” or “extremely low frequency” was used and many documents and relationships were obtained. The information obtained was analyzed using community detection algorithms and was plotted. Where the size of the nodes is proportional to the H-index, the lines between two nodes indicate that they are cited and the distance between them represents the collaboration between them. To carry out this representation an open source program, “Gephi” was used [40]. It covers several statistical tools for the treatment and visualization applying the community

detection algorithm. This program allows the reorganization of the vertices or nodes, their design, and their representation with different sizes and colors according to their properties, among other possibilities. The results obtained show that it is possible to determine the main areas of research activity, as well as identify the structures of the collaborative network in the field of ELF waves. Gephi allowed the export with the appropriate filters to select the communities to study, and the key-id community pair was obtained from this process. Then a refinement and clustering of the keywords was applied to avoid typographical and punctuation errors. Among the most common mistakes was the distinction that doubles the number of words, according to upper- and lower-case letters, the singular and the plural, the separation of words with space or hyphen, etc.

As a result of the large volume of data, some irregularities were observed during the information verification work—this problem is a frequent and common issue in the large databases and should be considered and corrected [41]. Thus, refinement is essential if you want to analyze the significant keywords used both globally and by community.

Figure 1a shows the initial search result, where the information debugging process has not yet been carried out. This debugging eliminates unnecessary information in order to establish an overview, reducing the number of documents and their relationships. In the debugging process, documents that do not have a relationship with the communities were eliminated. This does not mean that they are not referenced by other authors, but rather that there are no collaboration ties, which is why they are deleted. This figure shows many documents on the periphery, which do not show connections with the main collaboration centers.



(**a**) (**b**)

Figure 1. Representation of the communities investigating extremely low frequency (ELF). (**a**) Representation of the total untreated communities. (**b**) Representation of communities after debugging.

3. Results and Discussion

After searching for the keywords, a total of 12,436 documents were obtained with a total of 42,813 relations between authors, established from 1956 to December 2019. After carrying out the debugging process to avoid the collection of unnecessary information, the number of works was reduced to 40.73%, leaving 5028 documents and 72.2% of the total relationships. Figure 1b shows the total work after the purification process and the relevant statistical treatment—it shows the distribution of all documents in a total of 12 communities. Each publication is represented by nodes and its size depends on its relationships. This representation allows the establishment of a common metric with other search engines such as Google Scholar as well as a metric of the collaborations between the authors. An author who has a well published and is highly referenced, but who works by himself will only be represented by a smaller node than another less referenced work, but which has greater collaborations with others. In this figure, we can distinguish three zones in which the largest communities are located. One of these areas is located in the upper left of the figure where three communities can be distinguished, another area is the central area where two communities are observed, one of them

being the largest compared to the rest, and the last one is the area located in the lower part of the figure, where there are three communities that are related to each other, one of them being somewhat superior to the rest. Figure 2 shows the documents making up each of the communities according to their colors. This representation is necessary, because due to the interrelationships present in Figure 1b, it is difficult to precisely determine the size of each of these communities. Each community is assigned a representative title gained from the research topic of the documents forming it.

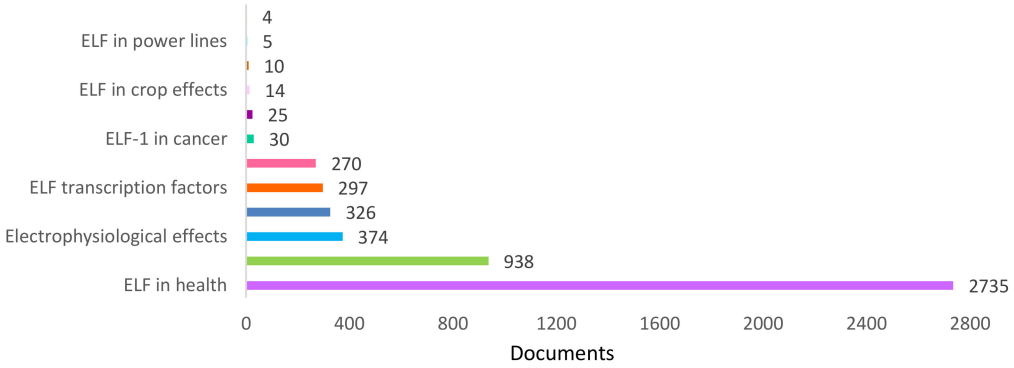


Figure 2. Representation of the distribution of the works in each of the communities.

After carrying out a preliminary analysis of each of the communities separately, it was noted that some communities have the keywords established in the search, but their meaning is very different from that considered in this work. These communities belong to the field of molecular biology and genetics: these are the ELF transcription factors, ELF-1 in cancer and ELF-1 in the brain. These communities have the same theme, the ELF-1 gene, a gene that encodes a transcription factor related to the specific E26 transformation and they are related to each other as indicated in Figure 3b.

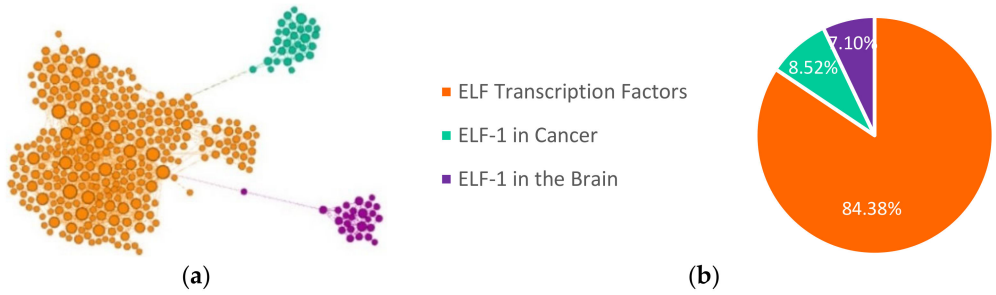


Figure 3. Representation of the ELF communities transcription factors, ELF-1 in cancer and ELF-1 in the brain. (**a**) Representation of the interaction of communities together. (**b**) Representation of the distribution of works in each community.

The largest community is the ELF transcription factors community, represented with orange, which encompasses 5.91% of the total work found. This community deals with general aspects derived from the ELF subfamily, one of the largest families of exclusive transcription factors of animals. The transcription factors that constitute this ELF group are ELF1, ELF2 formerly known as new ets-related factor (NERF), and ELF4 or myeloid elf-1-like factor (MEF). Some documents from this community deal with the necessary actions for the improvement of a new protein related to ELF1 [42], the study of new ELF1 transcription factors [43], the functions or standards of ELF4 factors [44], or how these ELF1 factors can be related to virus regulation for human immunodeficiency [45]. It is the central point from which the ELF-1 in cancer and ELF-1 in the brain communities derive, with sizes of 0.6% and 0.5% respectively. Figure 3b shows the number of documents present in each of these communities, considering that the largest volume is the ELF transcription factors community with 84.4% of the total work dealing with this issue, the other two communities are smaller than one tenth of the general

community, with the ELF-1 in cancer community being almost 1.5% more researched than the ELF-1 in the brain community.

The ELF-1 in cancer community relates to the general community (ELF transcription factors community) through work [46] which investigates a protein that interacts with the ELF gene, and that plays a key role in suppressing gastric carcinoma. The connection comes from the fact that some of the authors of this work have carried out other research present in the general community. Forty percent of the works of this community are published in journals related to cancer oncology and is research carried out in the last 20 years, from 1999 to 2019. The main theme of these publications is the relationship of the ELF1 gene with the development of various cancers. A relationship of this gene with cellular liver cancer has been established [47], and pancreatic cancer [48] and gastric cancer [49]. The articles constituting this community have a high number of references, as is the case of the most important work according to the nodes [50], published 3 years ago and with 202 references.

For its part, the ELF-1 community in the brain is related to the larger community through publication [51], where different genes present in the chick's retina are analyzed for vision in myopic blur conditions. The ELF1 gene is involved in the regulation of the vision system, together with other transcription factors, thus relating to other articles of the general community (ELF transcription factors). In the ELF-1 in the brain community, aspects derived from the ELF-1 gene in brain functions are considered, treating aspects such as the cloning of this gene [52], its topographic effects on the axon guide of the retina [53], or its importance in the hippocampus of the brain [54]. Most of the publications have many references in Scopus, the most important document by nodes [55] has 632 references.

After analyzing these three communities, they were discarded from the initial search when considering a theme that differs markedly from that existing in the rest of the communities, since it does not relate to ELF waves in any of its possible variants or applications. This is one reason showing that a search should not be established using only the keywords, since this fact does not guarantee that all the found documents belong to the same theme. It is vitally important to establish a detailed analysis of the communities found after the purification processes, to guarantee the effectiveness of the search performed.

The communities that really investigate ELF waves are represented in Figure 4. Considering that those formed by less than 2% of the total documents are represented together in black, under the heading "Other Communities". There are two communities that stand out for their size compared to the rest, the communities ELF in health and the lightning ELF phenomena. The ELF in health community have the largest publication percentage (58.50%) and show the highest concentration of related nodes. The lightning ELF phenomena community, publishing 20.06% of the total number of works, comes second in size and is related to nodes from other communities such as the ELF wave generation community or the natural ELF phenomena community.

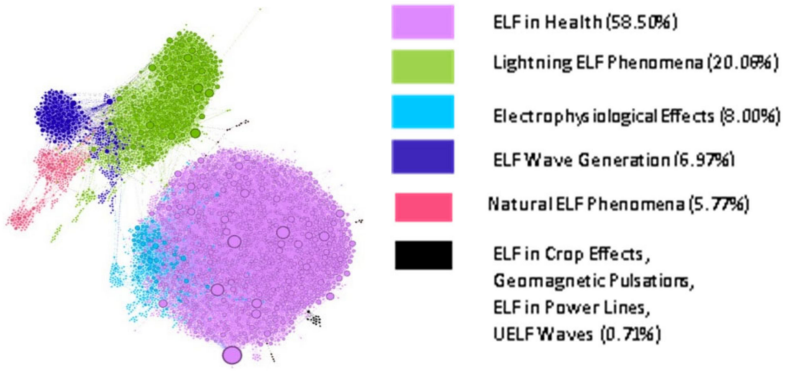


Figure 4. Representation of the communities investigating ELF waves.

Figure 5 shows the 20 global keywords that appear the most in the communities studied. The most repeated word was "extremely low frequency", one of the words used for the search with 509 repetitions, the following words were "electromagnetic fields" with 440 repetitions, followed by "magnetic field" and "extremely low frequency-electromagnetic field" with 358 and 252 repetitions respectively. All these words were among the 10 most-repeated keywords in almost all communities, considering them as general words.

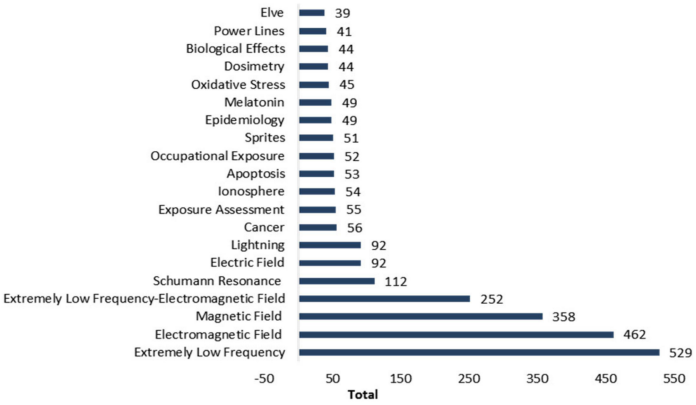


Figure 5. Representation of the 20 most-repeated global keywords.

Figure 6 shows all the keywords that appear in the documents of the communities studied, considering that their size depends on their number of repetitions. The most repeated words observed in Figure 5 are "extremely low frequency", "electromagnetic field", and "magnetic field". In addition, there are other words of the communities studied such as "human", "cancer", "elve" or "lightning". The variability of these words reflects the diversity of the fields that make up the communities studying ELF waves.

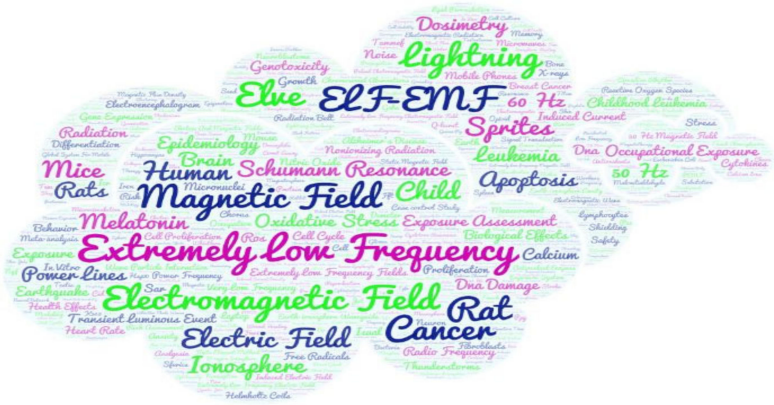


Figure 6. Representation of all global keywords.

3.1. Community Analysis

Next, the main nodes of each community were analyzed, considering their sizes and their most-significant contributions.

The community ELF in health consists of research studies tackling the influence of ELF electric and magnetic fields on human health. The isolated distribution of this community is represented in Figure 7a where the most important publications are observed according to the size of the nodes. The references, according to Scopus, of the three most-important nodes of this community were determined according to their size:

1. "Environmental Health Criteria 238: Extremely Low Frequency Fields" with a total of 15 references [56].
2. "Interaction of Static and Extremely Low Frequency Electric and Magnetic Fields With Living Systems: Health Effects And Research Needs" with 294 references [57].
3. "Biological Responses to Electromagnetic Fields" with 307 references [58].

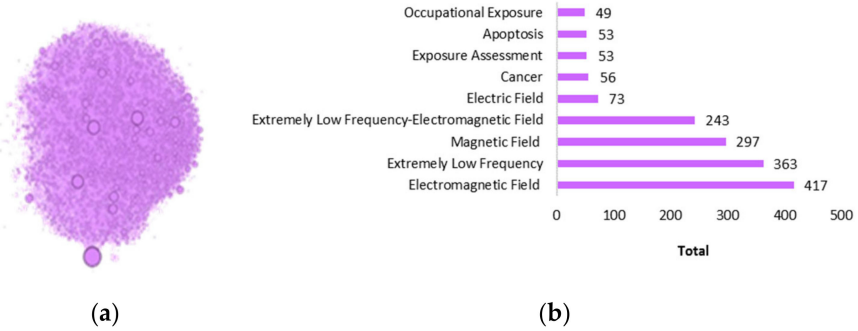


Figure 7. Representation of the ELF community in health: (**a**) isolated distribution of publications. (**b**) keywords of the community.

The 10 most-repeated keywords in this community are represented in Figure 7b, where "electromagnetic fields" ranks first with 417 repeats, followed by the search word "extremely low frequency" with 363 repetitions. The following words according to number of repetitions are very generic words of all communities, "magnetic fields" with 297 repeats, "extremely low frequency-electromagnetic field" with 243 repeats and "electric field" with 73 repetitions. Also, some words of the theme of this community such as "cancer" and "exposure assessment" appear 56 and 53 times respectively.

The population is exposed to an increasing exposure to different electromagnetic fields (EMF) ELF, so the need to establish the effects of these exposures is a widely researched topic, which explains why this community is the largest. The most important work of this community is [56]. It dates from 2007 and is closely related to publications from its own community and from other neighboring communities, such as the electrophysiological effects community. [56] is a monograph that presents different environmental health criteria (EHC) before exposure to ELF-EMF, evaluates the risks that such exposure entails, and intends to establish recommendations to national authorities on health protection programs. Its importance also lies in establishing the first division of the evidence found in health. It can be considered as "limited" evidence, since it is limited to a single study or there are unresolved questions about the design, performance, or interpretation of several studies. It can also be considered "inadequate" evidence for studies in which the presence or absence of an effect cannot be interpreted due to the presence of significant qualitative or quantitative limitations, or when no data is available. The following important publications in this community date from end of the decade of the 1990s [57] where various issues are considered mainly issues related to the determination of the existence of human health hazards arising from exposure to ELF fields, although several important biological responses are forgotten. Some of these answers are raised in [58], where a review and analysis of the studies based on the main cellular responses to the ELF-EMF is carried out, as well as their replication attempts. The quantitative aspects of exposure and the presence of cancers that have been correlated with these fields are discussed, since several epidemiological studies have concluded that such fields may be related to an increased risk of cancer [31].

A publication that should be noted for having numerous relationships with the electrophysiological effects community is [59], a book in which the biological effects of ELF emissions are considered from an energy point-of-view. It is stated that biological effects occur when a change in the environment causes some notable or detectable physiological change in a living system, and that these changes do

not necessarily have to be harmful to health. The body has mechanisms to adjust to various average influences, but when changes are accentuated for a long time it can happen that compensation does not occur, and unwanted effects appear. Therefore, determining the exposure times to these fields significantly marks the production of harmful effects on human health. In this book, a table is shown with the maximum permitted exposure values for ELF fields, as well as recommendations on the evaluation of the risks caused. From [28] it is extracted that for the exposure to these ELF fields to be evaluated, the fact that the exposure is imperceptible, has multiple sources, and may vary according to time and distance should be considered. In addition, the extraction of low-frequency signals does not occur naturally. There are numerous approaches to generating or collecting power from multiple low-frequency sources in the literature. These ecological generators convert the low-frequency mechanical shaking of ocean waves [60] or human motion [61] into alternating low-frequency electrical signals for energy collectors. One such energy collector, developed at [62], allows efficient energy collection from low-frequency voltage pulses, such as those typically generated by triboelectric or piezoelectric generators. The exposure period, which has an unknown duration and induction period, with no known appropriate exposure metrics and there are no biological data to rely on, should also be studied.

Jan Walleczek (1992) presents a review of the knowledge about the effects of non-thermal levels of ELF electromagnetic fields on the biochemistry and activity of immune cells [63]. The examination of the results suggests that the calcium molecule (Ca 2^{+}) plays an important role in the induction of these effects within the cellular field of the immune system. In another investigation, different cells associated with leukemia were exposed for EMF-ELF for 24 to 72 h, observing a 30% increase in cell proliferation after exposure [30]. The ability of these fields to induce DNA damage was also determined, measuring chain breaks and detecting an increase in DNA damage in all dose-dependent cell lines. Despite these findings, the precise mechanisms through which ELF fields increase cell production remain unknown and depend at least partially on experimental factors such as intensity, duration of exposure, and cell types used in the study. Therefore, a recurring theme in all the works is the urgent need to demonstrate a unique and unequivocal response induced by ELF-EMF, which is consistently reproducible in independent laboratories. Until this problem is resolved, the issue of biological responses to ELF-EMF will continue to be considered with great skepticism by the scientific community and extensively researched.

The community for lightning ELF phenomena is the second in size, with a percentage of 19% of the works studied and its isolated distribution is shown in Figure 8a. The documents of this community develop themes that encompass the propagation and characteristics of ELF electromagnetic resonance phenomena occurring in the cavity between the Earth's surface and the lower layer of the ionosphere, mainly due to the presence of lightning and storms. The references in Scopus of the publications represented by the most important nodes sorted by size in this community are:

1. "Schumann Resonance for Tyros: Essentials Of Global Electromagnetic Resonance In The Earth-Ionosphere Cavity" with 41 references [64].
2. "Sprites, ELF Transients, And Positive Ground Strokes" with 286 references [65].
3. "Criteria for Sprites and Elves Based on Schumann Resonance Observations" with 182 references [16].

The representation of the most-used words in the documents of this community is shown in Figure 8b, indicating that the most repeated is "Schumann resonance" with 96 repeats, being one of the most common resonance phenomena in the studied cavity. The next word is "lightning" with 89 repeats—this appearance is justified as the rays are the main causes of resonance phenomena in the studied cavity. "sprites", "ionosphere" and "elves", with 51, 41, and 39 repeats respectively are also among the 10 most-repeated keywords.

The work with the greatest relationships in this community is [64], a book dedicated to Schumann resonance (SR) that occurs in the cavity delimited between the Earth's surface and the lower edge of

the ionosphere. This phenomenon was predicted by W. O. Schumann in 1952 [6] and comprises signals from 7 Hz to 3 KHz. SR is the most-studied ELF resonant phenomenon, since it is a tool that permits establishing varied geophysical information. This information includes the climatic diagnosis [66], the study of global and continental thunderstorms [67], the determination of solar properties [68], and the global location of "red sprites" (optical phenomena in the mesosphere) that are associated with extremely powerful rays [16] or the relation with phenomenon's seismic [69] activity, with other possible applications.

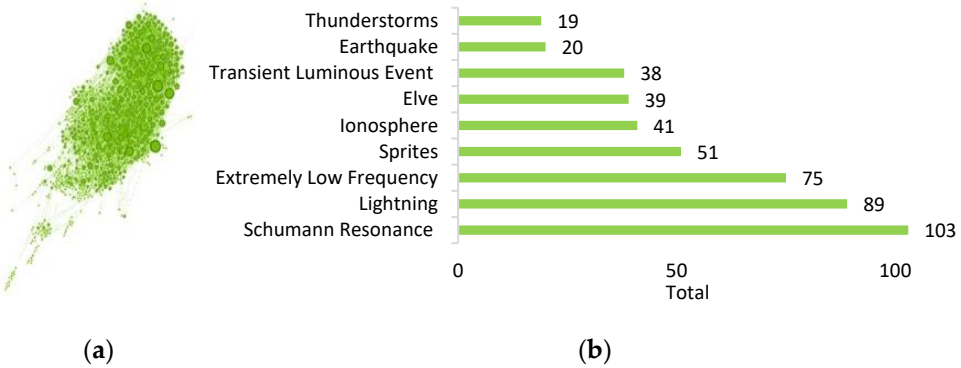


Figure 8. Representation of the lightning ELF phenomena community: (**a**) publications, (**b**) keywords.

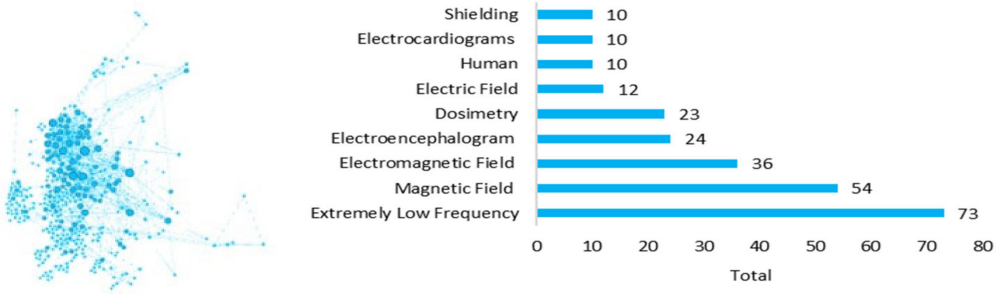
The work [64] is of interest for the treatment of the main properties of SR, its detection and the existing observatories, as well as the interpretation of the data obtained and the possible information that can be derived from them. Several works located among the most important nodes of this community are based on the study of ELF waveguide of the cavity formed by the Earth-ionosphere, as well as the determination of the propagation parameters of the waves from the electrodynamic properties of this cavity. One of them is [70], where a simple and approximate expression is obtained for the eigenvalues of the propagation of the ELF waves in the waveguide of the Earth's ionosphere, without considering the anisotropy due to the Earth's magnetic field. This publication forms the basis of others such as [71], which presents predictions for modal frequencies, wave phase speeds and quality factors that reasonably coincide with observations in the frequency range of SR (5–40 Hz).

Among the 10 most-important publications are several works where transient "sprite" events, or high-altitude luminous glows are studied [15]. The generation mechanisms proposed for these phenomena include the heating of environmental electrons through quasi-electrostatic thunder cloud fields, runaway electron processes driven by the same fields, heating by means of electromagnetic lightning, and others. These phenomena often coincide with lightning bolts of great amplitude and with transient excitations of SR [16]. The sprites sometimes appear to follow the horizontal progression of lightning in clouds and are not rare compared to typical lightning rates, as indicated in [65]. This work indicates the presence of sprites at distances of up to 1000 km, through the observations of the background RS established at the Wet Greenwich station (Rhode Island) and at the Yucca Ridge station (Colorado). The data of these stations were used in [72] for the detection of transient light events (sprites, blue jets, elves) of the large convective mesoscale systems (CMS) over US High Plains. The analysis of the detected sprites supported the hypothesis that these phenomena are almost exclusively associated with the positive lightning that occurs from Could Ground (CG) and that have peak currents substantially larger than those of a storm system. Later in [15], it was determined that sprites are related to intense discharges of lightning clouds from the ground (CG) and that they radiate electromagnetic energy at the ELF frequency (<1.5 kHz). In recent decades, the study of ELF signals has allowed us to understand transient luminous events (TLE) and the correlations between these phenomena. A more precise interpretation of these events and the type of lightning that originates them has been established: in [73] these events are studied, determining that their duration is less than 1 ms and that they occur in the lower ionosphere between 75 and 105 km of altitude, just after

the beginning of the cloud. A work to highlight is [74], where a global distribution of the rate of occurrence of these transient light events is established, observed by the FORMOSAT-2 satellite for 3 years. During the observation period, 80% of the registered TLE were elves (electromagnetic pulses generated by lightning strikes), and the remaining 20% sprites. Elves concentrate on the Caribbean Sea, the South China Sea, the eastern Indian Ocean, the central Pacific Ocean, the western Atlantic Ocean and the southwest Pacific Ocean; while sprites congregate over central Africa, the Sea of Japan and the western Atlantic Ocean. So, sprites are located mainly on the ground, as are lightning bolts, while elves are mostly found in the oceans and on the coasts.

The electrophysiological effects community presents 7.44% of the total studied works and its isolated distribution is shown in Figure 9a. In all publications of this community the discussed topics are the following: topics related to electrophysiological and cognitive effects on the human brain, the cardiac system and the nervous system, derived from exposure to ELF electromagnetic fields. According to Scopus, the references of the documents that represent the most important nodes considering their size are:

1. "Human Electrophysiological and Cognitive Effects of Exposure to ELF Magnetic And ELF Modulated RF And Microwave Fields: A Review Of Recent Studies" with 108 references [75].
2. "A Replication Study of Human Exposure To 60 Hz Fields: Effects on Neurobehavioral Measures" with 109 references [76].
3. "A Consensus Panel Review of Central Nervous System Effects of The Exposure to Low-Intensity Extremely Low-Frequency Magnetic Fields" with a total of 59 references [33].



(**a**) (**b**)

Figure 9. Representation of the electrophysiological effects community: (**a**) isolated distribution of publications, (**b**) keywords.

Although it was not developed until 10 years later, it should be noted that the number of references of the most important article is almost the same. The most-used keywords in the documents of this community are represented in Figure 9b, the search word "extremely low frequency" is the most-found in the documents (73 times). The following words by repetition number are "magnetic field" and "electromagnetic fields", with 54 and 36 repeats respectively. Both are of a general nature and are found in all communities. There is also a very characteristic word of this community: "electroencephalogram" with 24 repetitions.

Until the 1970s there was no awareness about how ELF fields affect the biological behaviour of human beings, developing some research in which the effects on animals were considered [77]. The concepts developed in works of this type allowed us to establish a simplified description of the interaction between an animal (or a conductive animal model) and an ELF electric field, as well as to develop qualitative estimates of different exposure situations and to be able to interpolate the results in human beings.

The document with the major node in this study is [76], which complemented and reinforced previous studies on exposure to low-frequency electric and magnetic fields and neurological

outcomes [78]. In [76] a combination of electric fields (60 Hz and 9 kV/m) and magnetic fields (20 pT) was used, and the cardiac constants by electrocardiogram (ECG) and the activity by electroencephalogram (EEG) of the study subjects were studied. The results supported the hypothesis that ELF electric and magnetic fields interact and influence human functions, with a decrease in cardiac constants and alterations in measures of brain activity. The effects are greater shortly after the application of the field and its disconnection, importing more changes in exposure levels than its duration.

The study of the interaction of ELF fields and living systems, as well as the risk of developing cancer cells has been extensively researched in the last decade, one example being [57]. The bidirectionality of these signals should also be considered. Studies have been established that consider cancer cells such as glioma or different types of cancers to generate ELF waves. In established studies of glioma patients, epileptic seizures are often seen due to the impact of the tumor on the physiology of the brain. This unexpected electrical activity can disrupt the functionality of the healthy neural network in the vicinity of the tumor mass and may contribute to seizures [79]. Breast cancer is one of the most common cancers worldwide, although its pathophysiology is poorly understood. Numerous single-cell electrophysiological studies have been developed, suggesting a link between bioelectricity and cell invasiveness. A pattern of activity with characteristics like those of random telegraph signal (RTS) noise [80] has also been recorded. A similar fact is observed in prostate cancer, one of the most common cancers in the male population, where its basic biological function at the cellular level is not yet fully known. In [81] the measurement and characterization of the electrical activity of PC-3 prostate cancer cell populations is presented, demonstrating for the first time the existence of a significant electrical pattern. This type of recording allows for the establishment of new, highly sensitive, real-time research pathways for the development of new, more-specific, and effective treatment strategies.

In the 2000s, reviews appeared that studied the electrophysiological and cognitive effects in humans after exposure to this type of ELF field as well as to radio frequency (RF) waves and the microwave frequency of mobile phones. One of these works is [75,82], the second in node importance in this community. The conclusions of this document expose the lack of unification of the beneficial or harmful effects against exposure to low intensity ELF electromagnetic waves. The author of this work, C.M. Cook, published another paper that studied the temporal evolution of physiological and cognitive effects derived from exposure to ELF magnetic fields and ELF-modulated radiofrequency fields. [82] reviews studies using techniques such as electroencephalography, event-related potentials, and positron emission tomography to investigate the effects of the electromagnetic field on human physiology and various measures of performance (cognitive, perceptual, behavioral). It also discusses the possible variables that are often not considered in human bioelectromagnetic studies, such as personality, individual differences, and the specific laterality of the ELF magnetic field and exposure to mobile phones on the brain. This review suggests that brief exposures may induce measurable changes in the electrical activity of the human brain, particularly in the region of alpha frequencies (8–13 Hz) over the posterior regions of the brain. Similar results are presented in [83], a publication that is among the 10 most-important nodes. It studied the effects of ELF sinusoidal magnetic fields (45 Hz) considering the EEG spectral analysis. It was observed that the average frequencies and the peak of the EEG increased in the frontal leads and that most of the changes were due to intermittent exposure, while a continuous exposure produced unimportant changes. The most significant effects are presented in the physiological measures, compared to the effects on performance, and it is possible that the behavioral measures are not sensitive enough to detect changes in brain function.

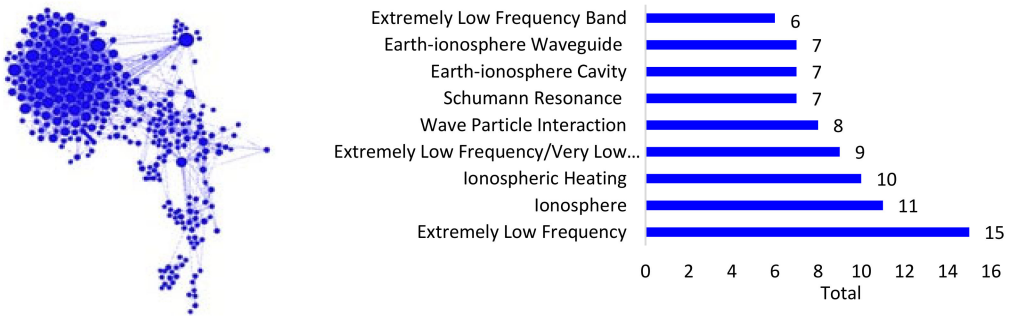
The effect of pulsed-ELF magnetic fields on the electrical activity of the human brain has also been considered [84]. The analysis of the results revealed a significantly higher occipital alpha activity. This study is not exempted from inconveniences, such as the exact determination of when these types of effects occur, the existence of interferences, etc., therefore subsequent work is necessary to verify the results obtained. An interesting job is [33]: it presents the effects of ELF magnetic fields on the nervous system and its functional changes. One of these changes is the perception of human pain, with a significant increase in pain sensitivity (hyperalgesia) after exposure to oscillating magnetic fields [85],

but without affecting the sensory threshold. The effects on the neurogenesis of the hippocampus suggest that exposure to ELF fields could be useful to improve the function of this area of the brain, which is mainly involved in learning and memory, as well as to facilitate functional compensation of age.

Another aspect to consider is if the exposure to EMF-ELF produces harmful cardiovascular effects [32]. The analysis of electrocardiogram data collected in studies such as [86] indicate that exposure to these fields exerts its primary influence during repolarization in the interval during which a flow of calcium ions occurs. These changes in the flow of ions can be a mechanism of regulation of the organism in the presence of ELF fields. During the last decades, several organizations have issued guidelines to limit occupational and public exposure to EMF-ELF, trying to prevent the acute effects they can cause. An example of such works is [87], where computational methods are used to estimate the dosimetry quantities of these fields. It is appreciated that the possible effects of these fields do not only depend on the duration of the exposure, but also on their intensity [86]. In all the works the same conclusion is reached, the results are quite variable and the mechanisms of action of the ELF fields are still poorly defined, so more experiments are needed to confirm the results.

The ELF wave generation community consists of works based on the generation of ELF waves through different mechanisms or sources, published from 1963 to 2019. Figure 10a shows the isolated distribution of this community, where the two most important are observed by size. The Scopus references of the first three nodes by size are:

1. "Sensitive Broadband ELF/VLF Radio Reception with The AWESOME Instrument" with 126 references [88], (VLF: very low frequency, AWESOME: atmospheric weather electromagnetic system for observation, modeling, and education).
2. "ELF and VLF Wave Generation by Modulated HF Heating Of The Current-Carrying Lower Ionosphere" with 95 references [4].
3. "ELF and VLF Radiation From The Polar Electrojet Antenna" with 67 references [1].



(**a**) (**b**)

Figure 10. Representation of the ELF wave generation community: (**a**) isolated distribution of publications, (**b**) keywords.

The most common keyword found in this community's documents is the search word "extremely low frequency" with 15 repeats, as shown in the keyword representation in Figure 10b. The following words: "ionosphere" and "ionospheric heating", with 11 and 10 repetitions respectfully, are both words that are typical of the theme developing the community.

ELF communications have been very important in recent years and continue to be researched today. These communications are very long-distance, as they involve large wavelengths and have been applied in very diverse fields, among which military communications stand out. An example of this is the application of this type of wave for communication between fixed stations and submerged submarines [89]. Many works have been developed and published based on the study of the generation,

propagation, and reception of ELF waves, since their discovery in the middle of the 20th century. Recently these communications have been used for emergency situations after natural or mining disasters [90], where other usual communication systems would not work.

For an antenna to be an efficient radiator it needs to have dimensions of the order of the wavelength being irradiated, so ELF antennas need large dimensions. This is what has driven the development of different types of ELF antennas, considering local and even spatial geographic characteristics, demonstrating that the D region of the ionosphere when illuminated by a powerful source can also act like an ELF antenna [91]. In recent decades, ELF waves have been shown to be generated through high frequency (HF) modulated heating (3–10 MHz region), which takes place in the D and E regions of the lower ionosphere (60–100 km). The modulated heating of the electron gas of these regions of the ionosphere results in the modulation of the corresponding conductivity tensor, based on the conductivity of the ionosphere depending on the temperature, and radiation is generated in the ELF band. This generation mechanism is the most common, with much research to prove it, such as [4], that represents the second-most-important node of this community. Another example from the literature of this type is [92], where the calibrated measurements of ELF waves generated by the HF-modulated heating of the ionosphere by the HAARP (high frequency active auroral research program) transmitter located in Gakona (Alaska) are presented. The generated signals were detected after spreading more than 4400 km in the Earth-ionosphere waveguide. [2] establishes the possibility of increasing the efficiency of the ELF generation by ionospheric modulation considering among other factors the ionospheric temperature and the existing modulated currents. In addition, characteristics of the ionospheric cavity where they are generated, such as the characteristic conductivity times of their region D, can be deduced from the ELF signals generated by the HF heating [91]. An alternative to the power modulation developed in the previous works is the geometric modulation, in which the ionospheric heating beam is geometrically directed at the desired frequency [93]. The waves generated in this way have improved amplitudes of 7 to 11 dB, and a directional dependence

The most important publication in this community for its existing relationships with other publications is [88], which presents the reception of natural and artificial ELF waves through the AWESOME receiver (atmospheric weather electromagnetic system for observation, modeling, and education), the sensitivity characteristics achieved, their frequency, as well as the precision in time and their cross modulation. The main author of this publication, Cohen, develops other works that are also located among the 10 most-important nodes of this community. One of them deals with the generation of ELF waves by striking two sources of ionospheric heating [3]. The resulting radiation pattern shows a strong directional dependence (up to 15 dB) that depends on the physical separation of the two sources. In [94] a 100-day record of ELF wave generation experiments is presented at the HAARP (High Frequency Advanced Auroral Research Project) facilities near Gakona, Alaska. It is observed that the generation during the local night is on average weaker but more variable, with a small number of very strong generation periods. The amplitudes of the signal from one day to the next can vary by up to 20–30 db. The third-most-important publication by its nodes is [1], which presents the characteristics of ELF radiation established by the polar electrojet antenna. In another work developed by the same authors almost a decade later, the results of the radiation produced by the Norwegian Tronsø heating antennas are exposed and the efficiency differences achieved in these cases are indicated, as well as their possible improvements [95].

The natural ELF phenomena community is formed by works based on the determination and study of the characteristic of natural ELF phenomena existing in the terrestrial magnetosphere. Figure 11a shows the isolated distribution of this community, the Scopus references of the three most-important nodes by size are:

1. “Broadband ELF Plasma Emission During Auroral Energization 1. Slow Ion Acoustic Waves” with 97 references [96].
2. “Propagation of Whistler Mode Chorus To Low Altitudes: Spacecraft Observations of Structured ELF Hiss” with 71 references [97].

3. "Interferometric Determination of Broadband ELF Wave Phase Velocity Within A Region of Transverse Auroral Ion Acceleration" with 84 references [98].

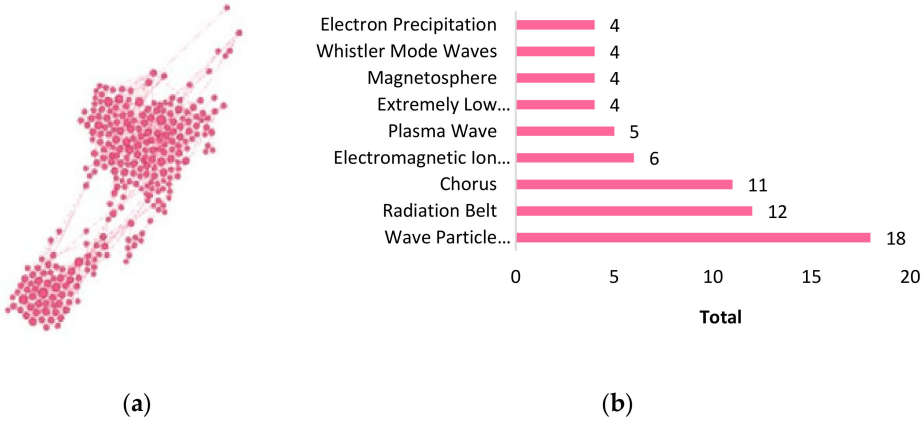


Figure 11. Representation of natural ELF phenomena community: (**a**) isolated distribution of publications, (**b**) keywords.

Figure 11b shows the 10 most present keywords in the works that make up this community, the first three are "wave particle interaction", "radiation belt", and "chorus", repeated 18, 12, and 11 times, respectively. All these words are characteristic of the theme developed in the community, as are most of those located among the 10 most-repeated.

The oldest publication of this community dates from 1969, and presents the magnetic noise existing in the magnetosphere, in the frequency range of 10 to 800 Hz, measured by the American satellite OGO 3 [25]. This document also establishes a statistical study of the spatial extent and frequency of occurrence of these signals, drawing conclusions such as that constant noise and noise bursts constitute two distinct populations. The terrestrial magnetosphere is considered one of the sources of ELF radiation par excellence, mainly due to the presence of energy phenomena such as lightning. A detailed analysis of the trajectories of the rays present in the magnetosphere, establishes its division into four different categories, considering: (1) the rays that were damped in their first jump from the equator to high latitudes, or that were trapped in the limit of the plasma pause for 1 s or less; (2) the rays that entered the plasmasphere, and that evolve to become plasmaspheric whistles, lasting tens of seconds; (3) the rays that are magnetospherically reflected at higher long latitudes at high latitudes and that evolve towards the emission of ELF waves, holding times close to 1 s; and (4) rays that are approximately aligned with the field, carrying most of the power of the chorus wave, and are damped at mid-latitudes within a period of 1 s. Each of these categories of rays behaves morphologically differently, and in most cases corresponds to different emissions [26]. In addition to the rays reflected in the magnetosphere, ELF emissions are formed by transverse acceleration ions (TAI) and explosions of the suprathermal electron burst (STEB), both taking place at the top of the auroral ionospheric regions. In the third-most-important publication due to the size of the nodes, the characteristics of the TAI-derived ELF waves are established, and their possible generation mechanisms are discussed [98]. These emissions of magnetospheric plasma have been observed by instruments located in spacecraft that orbit the Earth in all lines of the auroral field, and at all local times, from ionospheric altitudes. An example of this is [96], which represents the most important node in this community and where measurements are carried out by instruments located in the Freja spacecraft. These measures allowed to verify that ELF emissions are formed by several wave modes, the frequency range of 30–400 Hz is mainly dominated by slow ion acoustic waves (SIA), characterized by an almost perpendicular polarization and a small magnetic component. This emission is associated with large mass ions (O^+) of temperatures up to 30 eV and low temperature electrons (1–2 eV). Other components of wave mode, more difficult to identify are the alphanic waves or electric fields of great amplitude.

In [99], observations with this same satellite of 0–20 eV ions in the auroral ionosphere are presented. The results show a correlation between electronic precipitation and ionic heating for elements with energies below several hundred eV (energies associated with suprathermal electron explosions). So, the most intense heating events are strongly correlated with ELF waves and suprathermal electron bursts, the correlation being stronger for frequencies close to 500 Hz and electrons with energies of 500 eV. A statistical study of the ionic events presents in the plasma sphere, detected by the fast auroral snapshot explorer (FAST), indicates that 99% of the events found are associated with broadly extremely low frequency (BBELF) broadcasts or with electromagnetic ion cyclotron (EMIC) [100]. ELF events are the most numerous and cover 84% of the total, occur at all local times, with a peak near noon and a minimum near sunset. EMIC events are concentrated in the evening and at midnight, occurring at lower latitudes than the others.

Another type of event widely studied in this community are choir waves, or magnetospheric choir emissions, which occur in the ELF/VLF band (0.3–12.5 kHz) [27]. These types of emissions are the most intense of all those generated within the Earth's magnetosphere, occur during episodes of anisotropy of the distribution of energy electrons (10–100 keV), and contain information related to the mechanism generating them. In [101] the data obtained by satellite and those of a ground station are compared and a mechanism for generating these waves based on the interrelation of ELF noise emissions and discrete emissions under cyclotron wave-particle interactions is discussed. This model opens new possibilities for the explanation of the characteristics of the generation of these chorus waves such as their high growth rates or their relationship with the ELF hiss. This phenomenon is widely studied in [97]. It is a broadband electromagnetic emission in the frequency range from a few hundred Hz to about 2 kHz. It has been observed for more than 4 decades by terrestrial systems and satellite observations, and normally occurs at high geomagnetic latitudes. It should not be confused with the plasmaspheric whistle, which remains enclosed in the plasmasphere and never penetrates at low altitudes or to the ground, unlike the ELF hiss. The pattern of occurrence of the low-altitude ELF hiss has some similar properties to those of the choir emissions in whistling mode, both emissions have a local time distribution and similar frequency range. Chorus emissions occur predominantly at dawn and during the day, being considered a possible source of highly accelerated electrons in the Van Allen outer radiation belt. This emission can be propagated as an unconducted emission and it has been shown that subject to the action of the reflection of the magnetosphere and the degradation of its structure can lead to ELF hisses. The outer electrons of the radiation belts can undergo a gyrosonant interaction resulting in various modes of magnetospheric waves, including chorus waves outside the plasmasphere, ELF hiss, or electromagnetic waves of ion cyclotron within the plasmasphere [102]. The electrons of the radiation belts are subject to precipitation into the atmosphere due to the dispersion of the resonant passage angle by plasma waves during the recovery phase of a storm or during periods of prolonged activity of substorms. One of the publications among the 10 most-important by its nodes is [102], where a timescale of loss of electron precipitation is established due to the dispersion by each of the EMIC wave, chorus, hiss and wave modes, which can be 1 day or less.

Other communities: the group of other communities makes up less than 2% of the total work found, for this reason these communities are not studied in detail individually (Figure 12). This group includes the ELF community in crop effects (0.30%), the ELF in power lines community (0.11%), the geomagnetic pulsations community (0.21%), and the under extremely low frequency (UELF) waves community (0.09%).

The ELF community in crop effects is constituted by the publications that evaluate the biological effects of ELF electromagnetic fields on crops such as soybeans, corn, or seeds, among other grains. The most-represented keywords in the documents of this community are represented in Figure 12b, with the highest number of repetitions being "pulsed electric fields" with 8 repeats.

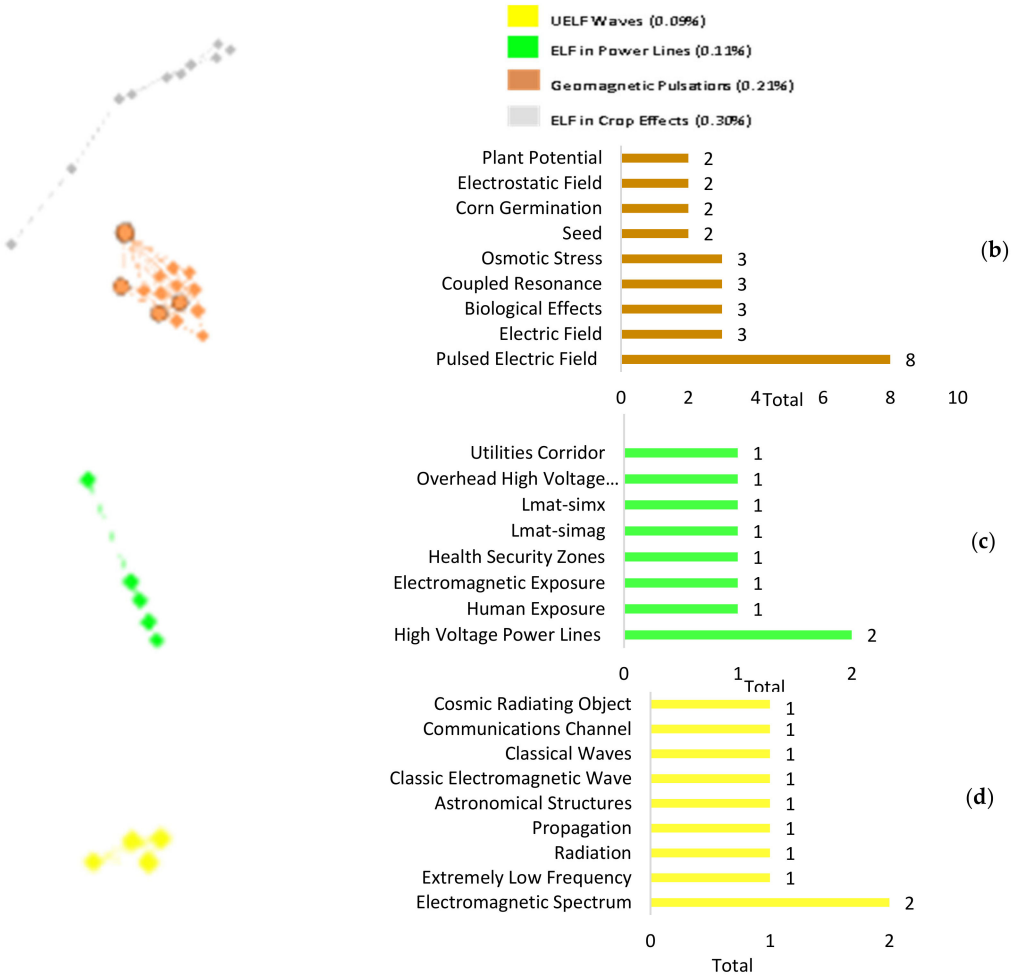


Figure 12. Representation of other communities: (**a**) isolated distribution of publications, (**b**) keywords of ELF in crop effects community, (**c**) keywords of ELF in power lines community, (**d**) keywords of under extremely low frequency (UELF) waves community.

The works of this community were developed between 2007 and 2017 and 80% of them were published in Chinese agriculture or engineering journals. The publication with the most important node is [103] with 34 Scopus citations, and studies the influence of the pulsating ELF electric field on the growth of soybean seedlings. In this publication the growth of plants is tested depending on the frequency of the fields to which they are exposed. It also allows establishment of future research where the measurement systems are improved, trying to apply them to other biological species in order to build a reproducible model globally.

The geomagnetic pulsations community was formed by publications developed between 1969 and 1983, being the decade of the early 1980s where 70% of the publications were carried out. It should be noted that this community does not have keywords due to the age of the documents and the magazines where they have been published. All works are based on the analysis and measurement of geomagnetic pulsations or variations of the Earth's magnetic field. The article of [104] represents the most important node of this community: it is the oldest and most referenced work, with 271 references. This publication is considered the basis of further research—it is a review article that establishes a classification of the pulsations according to their periods and the mechanisms of the sources that generate them. A detailed analysis of the characteristics and models of these pulsations had already been established at the end of the 1980s, which is why there are no further works.

The ELF in power lines community is one of the smallest, together with the UELF waves community, both formed by five works. All investigations have a theme based on the evaluation of the electromagnetic fields of transmission lines and very-high-voltage power lines. Figure 12c shows the 10 most-represented keywords in the documents, and due to the small number of publications that make up this community the number of repetitions of these words is small. The word that is repeated the most is "high voltage power lines" with 2 repeats. The rest only appear 1 time.

The most-important publication by its node is [105] and this has no reference in Scopus so far. This work is published in 2011, which establishes the evaluation of health security areas for exposure to overhead power lines. One of the rising trends in recent decades involves reducing exposure to artificial electromagnetic fields, with special emphasis on exposure to ELF electromagnetic fields, in order to discover if they have adverse health consequences. This document contains and identifies the safety zones of the magnetic and electric field around the high voltage power lines (HVPL), for the two types of HVPLs most used in Portugal (60 kV and 220 kV), developing a 3D simulation tool for these lines. The limit values established by the International Commission Non-Ionizing Radiation Protection (ICNIRP) of 100 μT and 0.4 μT for the magnetic field, and 5 kV/m and 100 V/m for the electric field are also considered.

Several research studies have been published studying the control of childhood cancer, commonly leukemia, and exposure to fields derived from lines at 60 Hz [106]. The evaluation of the effect of fields derived from these lines showed significant elevations in the risk of high exposure to them [107]. So, the determination of these safety zones helps companies and health authorities to reach agreements on this sensitive issue and is of interest to the general population

The UELF waves community is constituted by publications whose theme is the study of the electromagnetic spectrum in the range below the ELF band, the UELF band (under extremely low frequency). In the Figure 12d the 10 keywords that appear the most in the documents of this community are represented, establishing the same trend as in the previous community, of equal size. The word that is presented twice is "electromagnetic spectrum" and the rest appear only once. All the works of this community are developed by the same authors between 2017 and 2018, they are not very referenced and most of their references are carried out by other articles of the same community. The most important document is in nodes [108], and reflects on the existence of these signals, their behavior and the implications of waves with frequencies lower than one Hertz, which have so far been little studied. These waves are extremely long and relevant because they carry the information radiated by distant cosmic objects even larger than the Earth and which oscillate with frequencies lower than one cycle per second, and their interaction with matter (e.g., dust, gas, and particles) could create stationary structures in the Universe.

3.2. Author Analysis, Afiliations, and Countries of Investigation in ELF

In total there are 28,875 authors investigating different areas of ELF waves in 27 subjects in 114 countries. The twenty countries with the highest concentration of researchers contributing to their scientific publications on ELF waves have been analyzed and are represented in the Figure 13. The main contribution is made by the United States with 6023 researchers (20.86%), followed by China and Japan with 3072 (10.64%) and 2088 (7.23%) researchers, respectively. The following countries in the ranking belong to the European Union where Italy is the European country with the highest contribution of researchers with 1984 scientists (6.87%), followed closely by Germany with 1706 researchers (5.91%). The rest of the European countries have a contribution of scientists around 1512 from France (5.24%) and 1369 (4.74%) from the United Kingdom. The rest of the countries contribute less than 3% of the total of the authors, as is the case of Spain with 791 researchers (2.74%).

In Figure 14 the distribution of authors' participation can be observed according to the country of origin, according to a degradation of colors, the darkest being the one with the greatest contribution of researchers. There are 15.4% of other countries with a low-percentage contribution of less than 1% of the global number, such as Austria, Brazil, Taiwan, and Finland, among others.

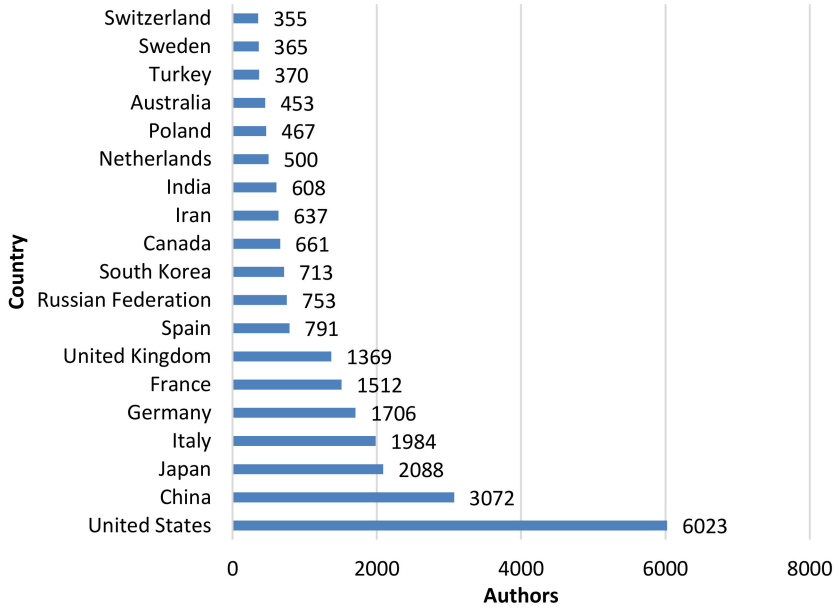


Figure 13. Representation of the 20 countries with the most participating authors.

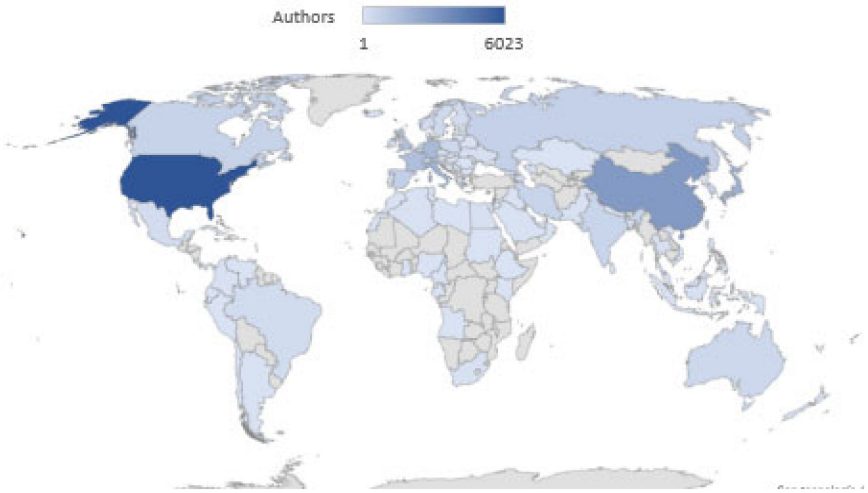


Figure 14. Distribution of authors per country.

The results show that both the United States and the Chinese states actively collaborate in the progress by establishing collaboration ties with other countries in order to move forward—this can be seen from the intertwining of the communities (Figure 2).

Table 1 shows a list of the 20 authors with the highest H-index according to Scopus in the ELF theme. If this table is compared with the countries with the highest contributions of authors, Figure 15, it is observed that there is no direct correspondence between the two, except for the United States. The first two authors with the highest H-index are from the United States, thus corresponding to the country with the highest contributions in authors in the search topic, with H-index values of 150 and 139 respectively. No Chinese author is among the 20 with the highest H-index, the first being in the 21st place, with a value of 93. The first Japanese author occupies the 16th position of the table with an H-index of 97. The Italian authors are found in positions 10, 12, and 18, with an H-index of 102, 99, and 95 respectively.

Table 1. Top 20 most-important authors by H-Index.

Indexed Name	H-Index	Citation_Count	Document_Count	University (Country)	First Publication (Year)	Community
Reíter R.	150	93,111	1530	University of Texas Health Science Center at San Antonio (United States)	2005	ELF in health
Pascual- Leone Á.	139	64,092	768	Harvard Medical School (United States)	2005	ELF in health
Egger M.	136	138,490	917	Institut fur Sozial- und Praventivmedizin (Switzerland)	2009	ELF in health
Winblad B.	130	70,964	1101	Karolinska University Hospital (Sweden)	2010	ELF in health
Boffetta P.	123	63,930	1212	Icahn School of Medicine at Mount Sinai (United States)	2005	ELF in health
Elliott P.	119	56,983	552	Imperial College London (United Kingdom)	2009	ELF in health
Pedersen N.	109	51,329	739	Karolinska Institutet (Sweden)	2005	ELF in health
Giles G.	105	50,474	1081	Melbourne School of Population and Global Health (Australia)	2017	ELF in health
Greenland S.	104	42,346	526	University of California (United States)	2005	ELF in health
Tumino R.	102	49,768	984	Azienda Ospedaliera Civile M.P. Arezzo (Italy)	2005	ELF in health
Sun D.	101	28,827	686	University College Dublin (Ireland)	2005	ELF in health
Franceschi C.	99	43,732	889	Istitutodelle Scienze Neurologiche di Bologna (Italy)	2014	ELF in health
das Neves J.	99	53,805	802	i3S - Instituto de Investigação e Inovação em Saúde, Universidade do Porto (Portugal)	2017	ELF in health
Waterfield M.	98	41,191	269	UCL (United Kingdom)	2005	ELF in health
Pukkala E.	97	40,078	731	Finnish Cancer Registry (Finland)	2005	ELF in health
Arai Y.	97	50,687	1071	High Energy Accelerator Research Organization (Japan)	2012	Lightning ELF phenomena
Cline D.	96	47,019	898	University of California (United States)	2007	Lightning ELF phenomena
Rizzuto R.	95	33,301	302	Universitàde gli Studi di Padova (Italy)	2005	ELF in health
Miller A.	95	35,519	471	University of Toronto (Canada)	2010	ELF in health
van den Brandt P.	94	35,660	472	Maastricht University (Netherlands)	2005	ELF in health

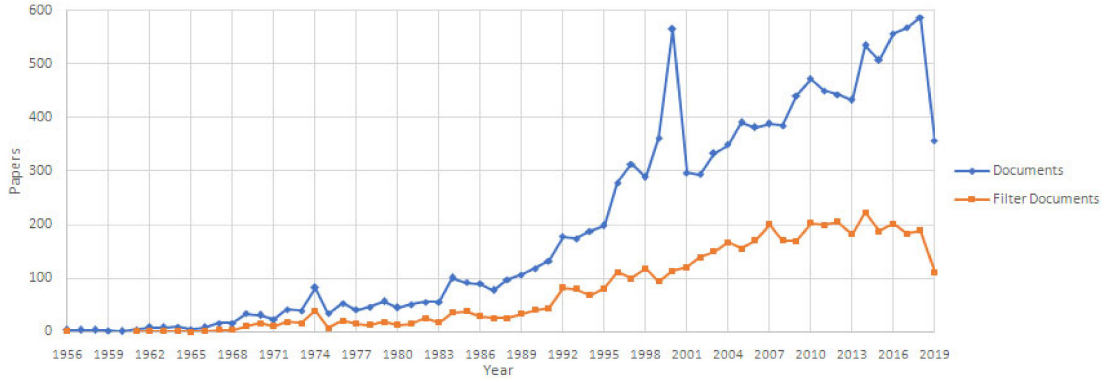


Figure 15. Representation of the temporal evolution of the documents published in Scopus on ELF.

If we relate the H-index values of the authors with the communities in which they investigate, it is observed that in the list of the top-20 only 2 communities participate, which coincide with the larger communities. Ninety percent of the authors publish in the largest community, the ELF in health community, which shows great interest between the relationship between the effects of ELF fields and health. Most of the authors of this table began to publish in this subject in 2005 and only two of these authors began their publications in 2017, although this does not imply that it is the first publication of these authors, as they may have previously investigated in other fields.

3.3. Analysis by Documents That Investigate in ELF

Figure 15 shows the temporal evolution of the documents published in Scopus, considering all the documents found with the search keywords (documents) as well as the documents that maintain relations in communities and are presented in Figure 4 (filter documents). The first documents were published in 1956, with an upward trend until 2018, at which point a decline occurs, as shown in 2019. In the evolution of the total documents there is an abrupt change, going from 362 documents in 1999, in which 159 are a source title, to 565 in the year 2000 (160 source titles). Subsequently the number of publications decreased to 297 in 2001 (160 source titles). This fact does not correspond to the number of source titles published in these years. If the major contributions in Scopus for 2000, Table 2, are carefully analyzed, it is verified that there is a substantial increase in contributions in 2000 and that three of them disappear in 2001, which contributed to 93 the previous year.

Table 2. Main contributions in 2000 of total ELF documents.

Source Tittle	Year		
	1999	2000	2001
Petroleum intelligence weekly	6	53	2
Middle East Economic survey	0	40	0
European chemical news	2	30	0
Petro strategies	2	29	0
Bioelectromagnetics	9	20	23

The main difference between the evolution of the total documents and the evolution of the documents considered by the communities studied is the year from which production exceeds 100 documents. In the total documents, this trend begins in 1989, while in the documents that are related by communities, this occurs seven years later in 1996.

The evolution of the documents considered in the communities also presents a temporary increase, although with less variability than that shown in the global document data. Until 1969, the number of publications on this subject was sporadic and less than 10 per year, the increase in research may coincide with the first investigations on geomagnetic pulsations. The most important node of the

geomagnetic pulsations community [104], was published in that year and lays the foundation for extensive further work. The number of publications does not increase to more than 100 until 1996. In this year several works located among the most important nodes of the natural ELF phenomena community have been published [98] and the lightning ELF phenomena community [73]. From that year on, the number of publications increases almost every year, reaching a maximum of 223 documents in 2014, in that year the publication of several of the works that represent the main nodes of the biological effects community takes place, such as [36]. This general increase may be an indicator that, once the relationships between authors have been established, these collaborations can be maintained throughout the professional life of the researchers or of the research groups consolidated in the subject. Thus, for the novel authors on this subject to acquire a high H-index value, they need to inherit the relationships of the research group to which they belong (Table 1).

The first publications of ELF waves date from 1956 and more than 66% of the publications have been published since 2000. One of the reason for this increase may be due to the increasing exposure of society to ELF electromagnetic fields and the need for determination of the effects that such exposure can have on human health, since from that time on, research with this perspective increases and more than half of the publications representing the most important nodes of health-related communities are developed such as ELF in health [28,59] and the electrophysiological effects community [33,75]. Another aspect of the last decades is the use of natural ELF signals for the diagnosis of the environment. This topic is of special interest due to its great applicability for the determination of global properties such as thunderstorms [15], among other things. In 2019 the number of publications decreased by almost 40% of those established in 2018—this may be because in that year 50% of the publications that make up the UELF waves community were developed [109] and they were not carried out years later.

In Figure 16, the distribution of the different publication formats of the documents found in the search for Scopus is represented. Ninety-one percent of the total documents are found as an article (77.86%) or conference paper (13.14%). These results are like those found in other works [37]. Other contributions can be found in review format (3.76%) and book chapter (1.78%), and publications in the rest of the formats form 2.23% of the total. In book format there are only 37 contributions (0.3%), although in each of the two largest communities (ELF in health and lightning ELF phenomena), the most-important node by relationships is a book ([56] and [64] respectively), with a high-references number as less than 41 in most of the cases.

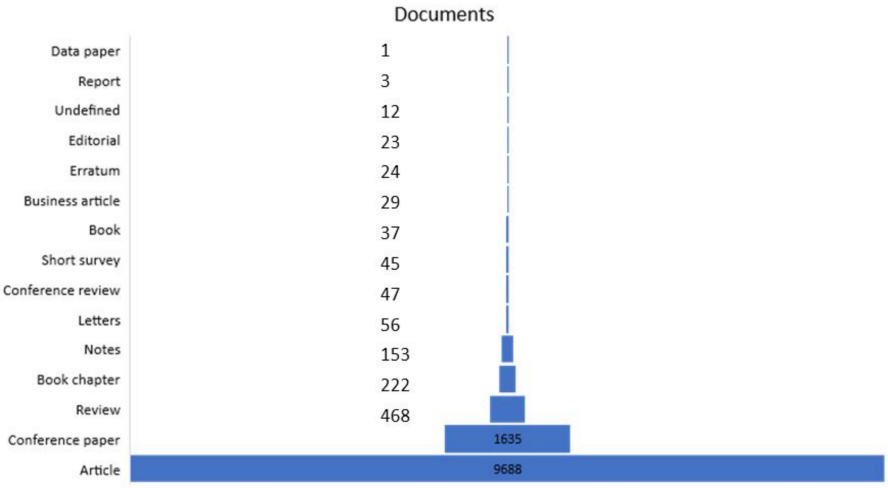


Figure 16. Representation of the type of documents published in Scopus about ELF.

English is the most-used language (92%) of the total publications, followed by Chinese (1.97%), French (1.74%), and German (1.7%). The rest of the languages have a representation below 0.5%, these being languages such as Japanese, Italian, Russian, Spanish, etc. It is common for the language by excellence in scientific publications to be English, since many scientific journals establish this in the

norms of their editions, in order to have maximum dissemination regardless of the country of origin or the headquarters of the publisher. Only China produces many scientific publications in its own language, such as Gaodianya Jishu/High Voltage Engineering, Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering, and Shengwuyixue Gong Chengxuezazhi/Journal of Biomedical Engineering, among others. A community where the publication in Chinese journals is more than 85% of the total documents is in the ELF in crop effect community, where the effect of ELF electromagnetic fields on corn [36] and soybean crops is investigated [103], among others. The increase of the population in China is a problem due to the lack of resources that can be derived, so the study of the exposure of crops to these fields can produce an increase in their growth to ensure the existence of food in continuous growth for the population.

The thematic areas most used for scientific dissemination are mainly medicine (14.76%), followed by biochemistry, genetics and molecular biology (12.66%), and engineering (12.38%). Areas of special interest are physics and astronomy (8.16%) and earth and planetary sciences (7.62%). In the rest of the areas, the contribution is less than 5%, as is the case of environmental science (4.24%) or agricultural and biological Sciences (3.76%). The large number of researchers in different disciplines such as medicine, engineering, physics, and astronomy allows us to state that the subject studied is a multidisciplinary issue of great impact and is currently being investigated [110,111].

4. Conclusions

In this work, research with the main theme of "ELF" signals, in any of its variants from 1956 to 2019, has been considered. After establishing the search for the keywords, 12,436 documents were obtained with a total of 42,813 relations between authors. After the use of bibliometric techniques, 5028 documents remained with 30,897 relations. These publications are carried out in different sub-themes, which are associated with 12 research communities, of which 3 of them had to be discarded after the analysis process despite having the same keywords, because they meant different concepts to the ones considered in this work. So, the documents studied are concentrated in nine communities or categories: ELF in health, lightning ELF phenomena, electrophysiological effects, ELF wave generation, natural ELF phenomena, ELF in crop effects, geomagnetic pulsations, ELF in power lines, and UELF waves. The ELF in health community has the highest concentration of documents (58.50%), followed by the lightning ELF phenomena (20.06%), electrophysiological effects (8.00%), ELF wave generation (6.97%), and natural ELF phenomena (5.77%) communities. The rest of the communities have a much smaller representation (0.71%), so they were not studied in detail in isolation. They do not have a main nucleus like the others, but they are constituted by small nuclei with ties of relationships between them and with other communities. In the spatial distribution of communities in Figure 2, a distribution in two regions is observed, one of them forms communities whose content is related to health (ELF in health and electrophysiological effects) and the rest of the communities are observed in the other region. The community for ELF in health as well as being the largest, is the most-researched at present and the one with the most work developed in 2019. The trend of these investigations is aimed at determining the most accurate way for possible effects of ELF fields on the body, either at the level cellular [8], on hematological parameters [112], or the immunity system [35]. A topic of special interest today is the relationship between ELF exposure and the development of relatively modern diseases such as sclerosis [113], stress, or depression. Research on ELF fields and cancer is numerous [114]—due to the impact of this disease today, the research is trying to control cancer cells with a specific ELF irradiation and lay the foundations for a possible personalized cancer medicine [115]. In the other community related to health, electrophysiological effect, five papers have been published in 2019. They are aimed at determining the effects of ELF-EMF on cognitive abilities such as learning or memory [116], as well as the modeling of the induced-ELF electric field in the human body and understanding its effects [117].

In the lightning ELF phenomena community, the investigations in 2019 focus on the modeling of the ionospheric cavity through various computational techniques with the aim of establishing a model as real as possible [118]. SR measures are still used for the reconstruction of global lightning activity [24]

or for the analysis of the effects of geomagnetic storms [119], coinciding most of the works in which the number of SR measurement stations should increase in the near future to correlate the records. The relationship between SR perturbations and seismic activity is also currently being investigated [21] in order to carry out an increasingly effective prediction of the presence of seismic phenomena and alert the population of their effects. In the last year, the ELF natural phenomena community has also been investigating, developing numerical models of plasma spherical emissions [120], as well as plasma nonlinearity [121]. In the wave generation community, research continues the generation of these waves through increasingly complex mechanisms [122]. In the rest of the communities, no work has been published during the year 2019, although most of the documents were developed in the last decade. These small communities are considered emerging communities where the greatest progress has been made, as most have appeared and fully developed in the last decade. An example of this is the community where the biological effects of ELF fields on crops are studied, where most of the papers have been published between 2008 [103] and 2014 [123]. These papers consider the exposure of different crops to ELF fields, which may be a discriminating factor for their growth. A similar fact occurs in another smaller community studied, the one related to the UELF spectrum. This community is formed by a small number of works developed since 2017 [124], so it is a very recent and little-researched topic. These are some of the reasons why these communities raise the possibility of developing many future works and research. The subject studied has great potential and can be applied to many fields, giving rise to a great deal of research and international publications of great interest. Despite this, there are communities that have disappeared, as is the case of the geomagnetic pulsations community, in which there have been no publications since 1983.

The most-repeated keywords globally correspond to the word used in the search: "extremely low frequency". There are also generic words that appear among the most-repeated in most communities individually: "electromagnetic fields", "magnetic fields", and "extremely low frequency electromagnetic fields". On a global level, specific keywords from each community also appear, such as "Schumann resonance", typical of the lightning ELF phenomena community or "cancer", a word located among the 10 most-repeated in the ELF in health community.

In total, there are 28,875 authors who investigate, 27 by subject, with the United States (6023 researchers) being the country that contributes the most researchers to this area, followed by China (3072 researchers) and Japan (2088 researchers). If the 20 authors with the highest H-index are analyzed according to Scopus in the search carried out, it is verified that it does not correspond directly with the distribution of authors by countries, with the exception of the first two that are from the United States, the country with the highest contribution of authors. The Chinese researchers are not among these top 20, the first being in position 21, while the first researcher from the next country for contributions, Japan, is in position 16. In addition, authors who publish in the most-represented community (ELF in health) show the great interest generated by the effects of ELF fields on health (58.50%). Of the 7849 centers that investigate ELF waves, the main collaborations are established between European centers, followed in isolation from Japanese, Chinese, and United States centers, this division coinciding with that of the countries that publish the most on this subject.

The temporal evolution of the documents published on Scopus shows a continuous growth from 1956 to 2018, at which point there is a small decrease as shown in 2019. This trend is shown both in the documents derived from the initial search, and in the documents studied after the purification and analysis process, observing in this line less fluctuations in time.

The main form of publication of the documents found is article format (77.86%), followed by conference paper (13.14%), review (3.76%), and book chapter (1.78%). The rest of the formats constitute 2.23% of the total published documents. As for the language, English (92.00%) is the most used to disseminate publications due to the standards of edition of the journals in order to have maximum dissemination regardless of the country of origin or the headquarters of the publisher. The second language used is Chinese (1.97%) since it produces a significant number of scientific publications with

international repercussions in their own language. The rest of the languages have a representation of less than <1.80%.

The conclusion of this work shows that research in this area is not completed and requires the development of works in which aspects related to their generation, the study of natural phenomena, and their relationship with health are considered, among other topics of interest. To carry out this objective the collaboration of all researchers is required. With their contributions, their applications and influence, they complete the knowledge about this type of field.

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