Mapping Manuel Sandoval Vallarta (1899–1977) Scientific Contribution

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Abstract
This paper employs network theory, mining data and bibliometric analysis when mapping the scientific contribution of Nobel Prize candidate; Manuel Sandoval Vallarta, the first and most renowned Mexican physicist and important figure in Latin American science. Vallarta died in 1977, and the existing literature is about his life and contributions to science but not about how those are still valuable today. This paper is the first to highlight, with mapping tools, that his contributions are relevant to the international community of cosmic rays (as he was pioneer and leader), quantum mechanics and relativity. These tools delivered three findings: Identify how he built his own field of study, same as universal knowledge. Unveil that the backward and forward Vallarta citations follow a scale-free network distribution. Determine social factors that benefited or affected his scientific activities—such as World War II interrupting Vallarta’s successful productivity at Massachusetts Institute of Technology. Furthermore, this study confirmed the interdisciplinary nature of the mapping studies of the scientist’s contributions using scientometric tools. As a result, several interesting questions arose throughout our research, some of which were answered from the history and philosophy of science. However, others need to be analyzed by experts in the fields of Vallarta. Mapping research sends an invitation to interdisciplinary dialogue/research between experts in different areas of study to better understand the process of knowledge production both, individual and collective.

Keywords Manuel Sandoval Vallarta (Mexico) · Mapping scientific production · Quantum mechanics and relativity · Cosmic rays · Network theory and tag-clouds · Bibliometric analysis · Interdisciplinary research

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1 Introduction

Leydesdorff et al. (2016) acknowledged four main stakeholders in research evaluation and management using bibliometric indicators: producers, bibliometricians, managers and scientists. The last one is significant to this work that focuses on mapping the scientific contribution of an internationally renowned scientist: Manuel Sandoval Vallarta (hereafter referred to as Vallarta).\(^1\) Our research included one more element: sociology, history and philosophy of science. This research line was proposed by Peritz and Bar-Ilan (2002) as an extension of the interdisciplinary nature of bibliometrics-scientometrics. We used three computational tools to map Vallarta’s production: Network analysis to determine how his fields of interest changed over time from 1924 to 1962. Bibliometric analysis to clarify the areas of the most cited articles including forward and backward citations. Finally, we incorporated a tag cloud and bigram analysis to ensure correlation with previous analysis based on the abstracts of his papers.\(^2\)

Why did we choose Vallarta? He was a world prominent scientist; Nobel Prize nominee that studied and worked with the world’s most renowned physicists. He was at the forefront of the cosmic rays field for many years and his breakthroughs helped open barriers in physics. He was the most remarkable physicist in Mexico and a major supporter of science in this country as well as Latin America; he campaigned for the peaceful use of nuclear energy at national and international levels and was the first chairman of the United Nations Atomic Energy Commission (1946). When he passed away in 1977, people considered his life’s work did too but the findings of this paper tell different, since the articles he published 90 years ago continue to be cited.

Historical books and articles have been published in recent years, revealing unexplored aspects of Vallarta’s life and analyzing his contribution according to the scientific scenarios of his time. However, no analysis of his academic outcomes has been produced in terms of bibliometrics, networks and data mining tools up until this article. And while our original idea was to approach his legacy without rigorous evaluation, the interdisciplinary nature of these studies granted us with information in contexts we did not expect. The elements we identified are detailed below along with The social history of science from which we began designing and developing this study:

1. **History of science** (social perspective). Vallarta’s educational background and expertise. His sudden shift from quantum mechanics and relativity to cosmic rays (due a geographical coincidence). His meeting in Mexico City during a vacation with a Nobel Prize physicist who was measuring cosmic radiation there. His employment at the Massachusetts Institute of Technology (MIT), his resignation (due to World War II) and his return to Mexico.\(^3\)

2. **Position and contribution as a scientist.** Vallarta’s scientific production and its international value and relevance. About his papers cited by Scopus, the top one on quantum mechanics and relativity was never quoted by himself, opposite to the three most cur-

\(^1\) His name was Sandoval on his father’s side and Vallarta on his mother’s side, but, he used to publish his papers like Vallarta.

\(^2\) These keywords analysis are similar to Bornmann et al. (2018), who used papers published by Eugene Garfield.

\(^3\) Some of the items shown correspond to the social history of science field, but in this work we separated them to show the areas in which our results emerged using the computational tools already mentioned.
rently cited articles on cosmic rays that he did mentioned several times. Citation to his work attests for the significance of his contributions. Still, some questions are open. His personal skills and abilities in physics.

3. **Social, political and economic context.** The impossibility of studying in England because of World War I. Favorable factors to stand out in his field: be acquainted with renowned physicists, received a two-year Guggenheim fellowship to study physics in Germany. Having leading-edge technical equipment, a worldwide unique computer, etc. Those that finished their thriving career despite the beginning of World War II. His return to Mexico (a developing country) and facing economic, institutional and scientific limits. His role as a promoter of science in Mexico and Latin America and his involvement as a diplomat in this country and abroad.

4. **Geographical (spatial) and cultural aspects.** Transportation and communication conditions that dificulted collaborations between colleagues working in the same spatial geographic environment—most foreign coauthors at MIT, most Mexican coauthors in Mexico. Political changes and cultural barriers. Competing interests.

5. **The philosophical features.** How Vallarta built his own field of study, in accordance with a knowledge flow network, these behave in a *scale-free* network distribution. Forward and backward citations exhibit a power-law behavior. Saam et al. (1999) coincidence in: Vallarta published a great deal of his articles in one of the best physics journals of the time, from which his most cited articles were taken.

6. **Interdisciplinary research.** When mapping Vallarta’s scientific contributions, questions inevitably arose that only their peers can answer. Two examples, what contributions did he make to the foundations of science that continue to be cited? Is Vallarta and Rosen (1932) paper related to EPR paradox? An example from the social sciences: Why was Vallarta the first chairman of the United Nations Atomic Energy Commission (1946)? These mapping tools invite to an interdisciplinary collaboration. 4

Next, we present a Vallarta’s life overview with the information required to interpret the graphs, tables and results obtained by running computer programs.

### 2 Background and Early Achievements in his Life

He was born in Mexico City in 1899 to a distinguished family. He completed undergraduate and PhD programs at MIT, where he was employed as teacher and scientific researcher. Between 1927 and 1929, he studied in Berlin and Leipzig, Germany, among the greatest physicists of this period. In Berlin, relativity next to Albert Einstein, electromagnetic theory with Max Planck, quantum mechanics with Erwin Schrödinger, and the exegesis of science with von Harnack. In Leipzig, he met Werner Heisenberg and Peter Debye. From 1929 to 1932, Vallarta published the results of his research, especially concerning the study of the unified theory of electromagnetism and gravitation proposed by Einstein upon which highly regarded physicists were focusing their attention (Del Río, 2018 and

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4 For this paper, four people from the following fields collaborated: general physics and the history of science, economics and philosophy of science, sociology, computer science and complex systems. For future research, we hope to invite an expert in the fields of Vallarta into our interdisciplinary team.
Mendoza, 1995). It is well known that his first contribution to quantum mechanics came up six months after this scientific discipline emerged.5

In 1932, his academic life changed when he met Compton in Mexico,6 who was completing a series of observations he had also made in Hawaii, New Zealand, Peru and Panama.7 Vallarta moved from the field of quantum mechanics and relativity to the field of cosmic rays. He felt greatly drawn to this subject as he realized that it could be an observational confirmation of the ideas on the primeval atom, through which; his friend Georges Lemaître (Riaza, 2010), sought to explain the origin and expansion of the Universe.8 Upon his return to MIT, Vallarta discussed his experience with Lemaître, and they immediately began developing a quantitative theory concerning geomagnetic effects of cosmic radiation (Mondragón, 1987).9 Their theory was easily successful, so Vallarta quickly gained an internationally privileged position.10 As a result, he promoted a number of international projects in this area—for example the establishment of observatories and labs—which helped bring institutions and scientists closer together across America. Especially in Latin America, he influenced the development of cosmic rays physics at both the individual and organizational levels (Minor, 2019).

In 1939, the theory developed was confirmed throughout numerous observations and was universally known as the Lemaître-Vallarta theory of cosmic radiation (Mondragón, 1999b, 116). One of the advantages of this theory is that it was extrapolated not only to the Earth’s magnetic field, but also to planets such as Mercury and Jupiter, other magnetically-fielded objects such as the Sun and other stars.11

The same year Vallarta held one of the best posts at MIT becoming a full professor of physics. He made a name for himself as one of the greatest teachers of theoretical physics.12 His excellent teaching and research were instrumental in MIT’s transformation from an engineering school to one of the world’s leading scientific research institutions.

5 In fact, Vallarta’s most widely cited paper was published with Rosen regarding relativistic quantum mechanics (Vallarta and Rosen, 1932). Moshinsky states that Vallarta’s “research laid a bridge between Einstein and Rosen, which, among other achievements, led to a critique of quantum mechanics implicit in the work carried out by Einstein, Podolsky, and Rosen” (Moshinsky, 1987, 47).

6 Mateos and Minor (2013) studied the different apparatus installed in several countries to measure cosmic radiation and alluded to those installed in Mexico since 1906, particularly those used by Compton and his colleagues as of 1932.

7 Vallarta accompanied Compton throughout his travels in Veracruz, Orizaba, Mexico City and Nevado de Toluca. Compton was measuring the intensity of cosmic radiation in different geomagnetic latitudes in order to prove that it was not electromagnetic radiation (photons), as proposed by Millikan. It seemed an interesting enigma to him to unravel the origin and composition of cosmic rays. Besides, how could the information carried by cosmic rays be obtained as they passed nearby or far away places if it was not possible to know their trajectories? (Mondragón, 1999a and 1999b).

8 If we consider the “primeval atom” idea as an “insight” then this paper supports the work of East and Ang (2021), in the sense that Vallarta changed his research field from Relativity and Quantum Mechanics to cosmic rays to look for evidence about the explosion of a single particle proposed by his friend Lemaître.

9 Their research led to the publication of several independent and collaborative papers. As will be noted later, the most highly cited papers to date are three joint papers in the Physical Review Journal.

10 Vallarta received the honor of being selected by the University of Toronto to write a book which he entitled An Outline of the Theory of the Allowed Cone of Cosmic Radiation (1938). Another acknowledgment he received for his leadership in the field of cosmic rays was an invitation to publish a paper entitled “Theory of the Geomagnetic Effects of Cosmic Radiation” (Vallarta, 1961), in Handbuch der Physik, the most prestigious encyclopedia of physics at the time.

11 Most citations to his work correspond to the years following his death, which might imply that he never realized the transcendence of his publications (Gall, 1987a).

12 When the United States shaped its science policy (Genuth, 1987).
By 1942, he decided to return to Mexico because the United States had joined the Second World War and MIT’s technological infrastructure redirected towards it leaving out individual research.\footnote{Vannevar Bush’s differential analyzer laboratory, through which (for instance), particle trajectories had been calculated efficiently, for instance, was being dedicated to military projects.} There were also restrictions for those not naturalized as US-citizens (as in his case) so he tried to focus on strengthening United States’ foreign policy in the Latin American region during that time (Minor, 2019).

Vallarta came back to Mexico at a time when the physical and mathematical sciences started to grow into scientific research’s professionalization and institutionalization.\footnote{At National Autonomous University of Mexico (UNAM), the Institute of Physics and Mathematics headed by Alfredo Baños Jr. (one of his MIT Mexican students), and the Graduate School of Sciences (Facultad de Ciencias) were founded in 1938 (Ramos-Lara, 2015). Ever since he worked at MIT Vallarta played a fundamental role in fostering physical science and mathematics: He visited Mexico to lecture, developing curricula, providing consultations in subjects like the acquisition of specialized equipment, training the first Mexican PhD’s after him, engaging actively in the Antonio Alzate Scientific Society (then, by 1930 called National Academy of Sciences), and even participating in various national and international events around Mexico (Ramos-Lara, 2005). He created the Mexican Society of Physical Science in 1943 (short-lived) and became the founding president of the current Mexican Society of Physics (Sociedad Mexicana de Física) established in 1950 (Lozano et al., 1982).} He did not only support the development of science and technology in Mexico, but also in other developing countries. His production dropped considerably during the time he fulfilled many national and international duties. Some of them were: President of the agency that the federal government created to promote scientific research in Mexico\footnote{Initially called the Scientific Research Promotion and Coordination Commission (Comisión Impulsora y Coordinadora de la Investigación Científica) (1943–1951), later renamed as the National Scientific Research Institute (Instituto Nacional de la Investigación Científica), today known as the National Science and Technology Council (Consejo Nacional de Ciencias y Tecnología/CONACYT) (Ramos-Lara, 2019).}; member of the Mexican National Nuclear Energy Commission (Comisión Nacional de Energía Nuclear) (1956),\footnote{Director of the National Polytechnic Institute (Instituto Politécnico Nacional/IPN), the most important higher education institution at that time, after the National Autonomous University of Mexico (Universidad Nacional Autónoma de México/UNAM); Undersecretary for Public Education (1953–1958); member of the UNAM’s Board of Directors; among other positions.} Mexican representative at the United Nations Atomic Energy Commission (which he led in 1946) and the International Atomic Energy Agency, etc.\footnote{Vallarta was not the only scientist to represent Mexico at international forums related to nuclear energy. There were also Nabor Carrillo [a civil engineer from what is today UNAM’s Graduate School of Engineering (Facultad de Ingeniería) and PhD in Soil Mechanics from Harvard University] and his MIT student Carlos Graef (also a UNAM civil engineer with an MIT doctorate), among others (Esqueda and Ramos-Lara, 2013). The term that Minor uses in order to name the diplomatic functions Vallarta carried out was science diplomat, which alludes to the role played by an expert in spaces devoted to international discussions where diplomacy is used to address scientific issues (Minor and Vargas, 2015).} President of several international commissions on cosmic radiation\footnote{President of the International Commission on Cosmic Radiation Units and Measurements of the International Union of Pure and Applied Physics (1953); President of the Latin American Council on Cosmic Radiation in Brazil (1960); President of the Latin American Council of Space Physics (Rebolledo 1987, 157–173).}; chairman of the United Nations Atomic Energy Commission (1946); chairman of the Bose Institute Reviewing Commission in Bombay, India (1948); member of the founder Committee for the Advanced School of Theoretical Physics of the University of Trieste—with Oppenheimer, Weisskopf, Bohr, Soloviev y Abdus Salam—to help first-rank theoretical physicists in developing countries (Chronicle 1965), among other positions. President of several international commissions on cosmic radiation, etc.; chairman of the United Nations Atomic Energy Commission (1946); chairman of the Bose Institute Reviewing Commission in Bombay, India (1948); member of the founder Committee for the Advanced School of Theoretical Physics of the University of Trieste—with Oppenheimer, Weisskopf, Bohr, Soloviev y Abdus Salam—to help first-rank theoretical physicists in developing countries (Chronicle 1965), among other positions.}

\footnote{There were also restrictions for those not naturalized as US-citizens (as in his case) so he tried to focus on strengthening United States’ foreign policy in the Latin American region during that time (Minor, 2019).}
Throughout the last three decades of his life, one of Vallarta’s main priorities was to channel nuclear energy use for best and peaceful purposes, so he took active participation in national and international forums. During those years, he also published various essays regarding science’s impact on society and how it had become a political, industrial, and military resource. In general terms, he would refer to the moral responsibility scientists had to face regarding the application of their discoveries (Gall, 1987b).19

Vallarta died in Mexico City on April 18, 1977. This unfortunate event meant a great loss to the Mexican scientific community. In honor of his memory and legacy as an international scientist and promoter of Mexican science, physicists Alfonso Mondragón (then a senior professor-researcher at UNAM’s Institute of Physics) and Dorotea Barnés; edited Vallarta’s full production in the book Manuel Sandoval Vallarta. Obra científica (858 pages). It was issued in 1978 to commemorate the anniversary of his passing. They also obtained the license of all journals where Vallarta had published (Mondragón & Barnés, 1978).

From this book we collected the data of the backward direct citations of his work to carry out the bibliometric analysis, and the abstracts to be analyzed with data mining. The data was completed with forward citation tracking using Scopus, one of the largest and abstract citation databases in the world in the research field, which is highly reliable due to peer-review.20 Tag cloud analysis was performed using software designed and developed by Gustavo Carreón, one of the authors of this paper. This work contributes to the recent efforts in México to analyze scientific production in the field of physics (Del Río et al., 2020, Lancho-Barrantes and Cantú Ortiz, 2019).

3 Bibliometric Analysis of Vallarta’s Scientific Work (1924–1962)

Our information source to create the backward citations database was taken from the Mondragón and Barnés book Manuel Sandoval Vallarta. Obra científica (1978). It was divided into 3 sections21:

1. The papers in which Vallarta published the results of his original research (national and international journals).
2. Essays and lectures on scientific subjects.
3. Vallarta’s curriculum vitae.

The first section in chronological order from 1924 to 1962.

We used the information contained in the first section to conduct an analysis of his scientific research. We built the historical network database incorporating each record one by one, because there isn’t exist a digital version. This was a slow and meticulous task that required the citation revision of each Vallarta’s article. Figure 1 show the journals in which

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19 Although he did publish several papers in Mexico, both independently and with different collaborators, the most widely cited papers to date continue to be those which he co-authored with Rosen and Lemaître.
20 Mendoza, Acatitla and Urbina (2019) used bibliometric tools to analyze the scientific work of Mexican physiologist Arturo Rosenblueth, PhD from Harvard University and Vallarta’s friend.
21 This book was sponsored by the Mexico’s National Institute of Nuclear Energy and the UNAM’s Institute of Physics. The publishers of the book were UNAM and the National Institute of Nuclear Energy.
he published the largest number of papers: Physical Review, Journal of Mathematics and Physics, Nature, and Proceedings of the National Academy of Sciences USA.

Figure 1 demonstrates that the Physical Review journal published most of Vallarta’s papers consistently throughout his scientific career. This journal widely disseminated the results of his research pertaining to relativistic and quantum physics and to cosmic rays. During the final years of his career in which he again gained interest studying gravitational theory; Physical Review, continued to publish his work. This journal also describes the contribution that Vallarta’s colleagues in Mexico made to the study of cosmic rays.

The distribution of papers published by Vallarta from 1924 to 1962 is shown in Fig. 2. Periods of great productivity can be appreciated. The first one alludes to a period in which he had an interest in quantum mechanics and relativistic physics (until 1932), whereas the second one refers to his contributions to the study of cosmic rays—each period presents a maximum of productivity. A reduction in the amount of papers can be noted during the 1940s. This coincides with the World War II and his return to Mexico to carry out tasks as a government official to develop science, technology, and education. Becoming a science diplomat attending at international forums, particularly those related to developing nuclear energy.

This section presents the results of the bibliometric analysis using Scopus database, referring to 36 papers that Vallarta published between 1926 and 1958. The results are shown in Table 1.

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Table 1 shows that the four papers with the largest number of citations were published in the Physical Review journal; one in 1932, one in 1933, and two more in 1936. This, during his early stage as a researcher. He had already received his PhD from MIT in 1924. After that, he traveled to Europe to continue his studies, and in 1929 he returned to MIT as a faculty member. Vallarta’s h-index (provided by Scopus), corresponding to 5 out of 36 documents with 218 citations, should also be noted. We have no opinion on this value as we agree with Leydesdorff et al. (2016) about the difficulty to interpret it.

It is known that Vallarta was a great admirer of Einstein’s theory of general relativity and a severe critic of his ideas about the unified field, since he considered that a theory

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22 It is noteworthy that Physical Review is also the journal where he is cited the most, although the maximum corresponds to Advances in Space Research. On the other hand, L’Annunziata (2016), in his book about Radioactivity, cites 20 Vallarta’s articles.

23 Analysis conducted between October 2019 and May 2022.

24 Google Scholar shows that the first three papers that Lemaître and Vallarta published together have a larger number of citations (since it is a more open bibliographic database) and is interesting to note that indicates a relatively proportional numerical trend, i.e., from 59 to 190, from 21 to 115, and from 14 to 85.

25 The frequency of citations in Vallarta’s articles (1971–2022) follows the power law behavior. That is, many Vallarta’s papers are rarely cited, and a few papers receive many citations. The behavior refers Lotka (1926): a low percentage of authors receiving many mentions and a high percentage of authors mentioning only a few. Also, Saam and Reiter (1999): many scientists publish very few articles and books, while very few scientists publish many.

26 The h-index is a system that seeks to measure the impact of any scientist’s academic publicativity in relation to the number of citations his papers have received. It was proposed by the Spanish physicist Jorge Hirsch, working at the University of California. This index shows that a scientist has an h-index if he has published h papers with at least h citations each. The h-index of some of Vallarta’s collaborators is as follows: Carlos Graef’s h-index is 2 with two papers, Alberto Barajas is 1 with one paper, Lemaître is 6 with twelve papers, Rosen is 27 with 130 papers, Kusaka is 4 with eight papers, Bouckaert is 2 with 2 papers, and Birkhoff is 26 with 106 papers, among others (data from May 9, 2022). Another paper will soon present an analysis comparing these figures.
of that kind should be first developed for gravitation and electromagnetism. By the end of the 1920s, he published some papers about this issue (one with Wiener). In 1932, one with Nathan Rosen, “The relativistic Thomas–Fermi atom,” which benefitted Rosen as it bridged his connection with Einstein at Princeton. Years later, Einstein, Podolsky, and Rosen published the famous paper concerning quantum mechanics (Moshinsky, 1987, 47). Table 1 show that until 2022 this was the paper with the largest number of citations.27

Figure 3 indicates the number of citations the three most cited art icles received per year until May 6, 2022. Figure 3a corresponds to Vallarta and Rosen (1932). Figure 3b relates to second paper with the largest number of Vallarta citations that was co-authored with Georges Lemaître in 1933—Lemaître and Vallarta, “On Compton’s Latitude Effect of Cosmic Radiation,” Physical Review, 1933, 43, 87. Contrary to the earlier paper with Rosen, this one has been the most extensively cited paper in recent times.28 The third and last paper hereby analyzed (Fig. 3c) is Lemaître and Vallarta, “On the Allowed Cone of Cosmic Radiation,” Physical Review, 1936, 50, 493.

Vallarta’s papers have started to gain relevance in recent years. Figure 4 shows the annual distribution of the number of citations to the 36 papers presented in Scopus. It can be seen that those papers started to be cited in 1971 and most citations have been made since his death in 1977. It should be noted that some of them, like the three presented above, have maintained relevance.

The peak observed in 2016 is because L’Annunziata (2016) cites 20 Vallarta’s articles in his book on Radioactivity.29 Sometimes these events raise the papers citations. If this data is clustered by decades, growth becomes (program auto-adjustment shows a quadratic curve, until 2019) as in Fig. 5. Fig. 6 shows the selfcites:

We can see that Vallarta’s articles cited by himself in cosmic rays are also the most cited internationally (see Table 2). However, his article with the most citations reported by Scopus (on relativity and quantum mechanics) was never cited by Vallarta. There are three other articles that he never quoted, which are in the top 10 of Scopus: Vallarta (1933), Forbush-Gill-Vallarta (1949) and Barajas-Birkhoff-Graef-Vallarta (1944).

Our results agree with Saam et al. (1999) who claim “the higher the reputation of the scientist, the quality of the article, or the quality of the journal the article was published in, the higher the probability of receiving citations more frequently”. Vallarta was a much referenced cosmic rays science leader in the 1930s.

27 On May 6, 2022, Scopus was consulted again and the last 3 cites were: Y. Ikabata, H. Nakai (2021), “Picture-change correction in relativistic density functional theory”, Physical Chemistry Chemical Physics, 23(9), 15458–15474. H. Barman, A. Rahaman, S. K. Jha (2021), “On the reformulation of the Thomas–Fermi model to make it compatible with the Planck-scale”, Modern Physics Letters A, 36(19)2150130. D. N. Voskresensky (2021), “Electron-positron vacuum instability in strong electric fields. Relativist semiclassical approach”, Universe, 7(4)104. It was found three authors quoting Rosen-Vallarta (1932), which has numerous citations: P. Pyykö (1978) Advances in Quantum Chemistry (343 quotes), Z. Sabir et al (2018) Applied Soft Computing Journal (130 quotes), A. Nagy (1998) Physics Report (120 quotes).

28 The paper in which it is cited, J. C. Gosse and F. M. Phillips, “Terrestrial in situ cosmogenic nuclides: Theory and application,” Quaternary Science Reviews 20 (2001) 1475–1560, has the largest number of citations, totaling 1431. The next one has 158 citations: J. F. Ziegler, “Terrestrial cosmic ray intensities,” IBM Journal of Research and Development 42 (1998) 117–139. The third one has 74 citations and is K. D. Bidle, S. Lee, D. R. Marchant, P. G. Falkowski “Fossil genes and microbes in the oldest ice on Earth,” Proceedings of the National Academy of Sciences of the United States of America 104 (33) 2007, 13455–13460.

29 It should also be taken into account that the 2016 International Conference on Ultra-High-Energy Cosmic Rays (UHECR 2016) was held in Kioto.
Analytical network methods are significant to model and analyze indirect effects (direct effects can be analyzed using classical statistics). By calculating the parameters, we obtained information about the system as a whole (Zweig, 2016). Connections are important, but also the segregated network, because it reveals levels and concepts of organization that aren’t easily found otherwise (Newman, 2010). Temporal fluctuations in the network, called dynamic networks, also provide information about the behavior of the network structure (Barzel & Barabási, 2013). 30

Network study mainly focuses on two aspects: its structure, i.e., the form in which the elements are linked together and its dynamics, i.e., the changes that occur in its structure over time (Solé, 2009). For the purpose of this study, elements were identified as nodes or vertices and the relationships between them were called edges or sides. In a scientific collaboration network, for instance, the nodes could represent individuals or institutions and the edges could represent the collaboration links between them, for example, in projects, papers, books, or lectures (Baker, 2013). A given structure in a scientific collaboration network can explain certain peculiar qualities regarding the way in which activity is conducted in a certain place and the changes it undergoes. It could give way to other characteristics that had not been contemplated originally, thus the importance of studying Vallarta.

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| Paper                                                                 | Year | Citations |
|----------------------------------------------------------------------|------|-----------|
| Vallarta, M. S. & Rosen N., “The Relativistic Thomas–Fermi Atom,” Physical Review, 1932, 41, 708 | 1932 | 64        |
| Lemaître, G. & Vallarta, M. S., “On Compton’s Latitude Effect of Cosmic Radiation,” Physical Review, 1933, 43, 87 | 1933 | 59        |
| Lemaître, G. & Vallarta, M. S., “On the Allowed Cone of Cosmic Radiation,” Physical Review, 1936, 50, 493 | 1936 | 21        |
| Lemaître, G. & Vallarta, M. S., “On the Geomagnetic Analysis of Cosmic Radiation,” Physical Review, 1936, 49, 719 | 1936 | 14        |
| Forbush S. E., Gill, P. S. & Vallarta, M. S., “On the Mechanism of Sudden Increases of Cosmic Radiation Associated with Solar Flares,” Rev. Mod. Phys., 1949, 21, 44 | 1949 | 10        |
| Lemaître, G., Vallarta, M. S. & Bouckaert L., “On the North–South Asymmetry of Cosmic Radiation,” Physical Review, 1935, 47, 434 | 1935 | 5         |
| Vallarta, M. S., “The Interpretation of the Azimuthal Effect of Cosmic Radiation,” Physical Review, 1933, 44, 1 | 1933 | 4         |
| Vallarta, M. S., “On the Longitude Effect of Cosmic Radiation,” Physical Review, 1935, 47, 647 | 1935 | 4         |
| Vallarta, M. S., Graef, C. & Kusaka, S., “Galactic Rotation and the Intensity of Cosmic Radiation at the Geomagnetic Equator,” Physical Review, 1939, 55, 1 | 1939 | 4         |
| Barajas, A.,-Birkhoff, G. D., Graef, C. & Vallarta, M. S., “On Birkhoff’s New Theory of Gravitation,” Physical Review, 1944, 66, 138 | 1944 | 4         |
In this section, we studied the structure of the networks to analyze how the backward citations evolved each time Vallarta published an article. We found very significant changes between 1932 and 1933, and between 1939 and 1940. 1932 was the year he turned into cosmic rays, a radical departure from quantum mechanics and relativity. We observed the formation of four new networks; two of them are the most cited articles today. On the other hand, cosmic rays productivity peaked in 1939, and the following year, a sharp decline. Next, we will explain the database construction (backward and forward citations).

As already mentioned, our backward citation database was built on the basis of Mon-dragón and Barnés (1978). In total, there are 51 Vallarta’s articles and 512 articles he quoted from 1924 to 1962. 31 The database information for forward citations is from Scopus (references looked up in May 2022) and is 36 documents containing 218 citations. Both databases were organized by authors’ name and year of publication. Vallarta’s articles added the letters a, b, c, d, and e when there were several published in the same year. In this way, each item is completely distinct from the other items. An example is shown in Table 3. Networks were created with the Cytoscape 3.7.2 program.

To analyze Vallarta’s scientific research, we used a directed network with the references that Vallarta cites in his research as nodes.

The structure of the network is shown in Fig. 7. The three networks represent the evolution of his publications from the beginning (1924) to 1930 (Fig. 7a), there were none in 1931, 1932 (Fig. 7b) and 1933 (Fig. 7c). We added the amplification of a network section to observe its structure (Fig. 7d). From an early stage in his career, Vallarta worked

31 Mondragón’s book includes 60 Vallarta’s articles, but not all of them have references.
**Fig. 4** Distribution of the Number of Citations to Vallarta’s Scientific Work per Year. (By May 2022, Vallarta had already been cited) Source: Developed by the authors using Scopus data on 13 May 2022

\[
y = 4.8571x^2 - 13.143x + 24.2
\]

\[R^2 = 0.9768\]

**Fig. 5** Number of Citations that Vallarta’s Scientific Work Has Received per Decade. Source: Developed by the authors using Scopus data on January 15, 2020

**Fig. 6** The number of references that Vallarta cited in his papers (blue), the number of Vallarta’s papers cited by himself (red). Source: Developed by the authors using data from Mondragón and Barnés (1978)
Table 2 Most frequent Vallarta’s articles cited by himself vs most cited Vallarta’s articles in Scopus data base

| Most frequent Vallarta’s articles cited by himself | Most cited Vallarta’s articles (Scopus) |
|---------------------------------------------------|---------------------------------------|
| 1. Lemaître, Vallarta (1936). “On the Geomagnetic Analysis…” | Vallarta, Rosen (1932). “The Relativistic Thomas–Fermi Atom” |
| 2. Lemaître, Vallarta (1936). “On the Allowed Cone…” | Lemaître, Vallarta (1933). “On Compton’s Latitude Effect…” |
| 3. Lemaître, Vallarta (1933). “On Compton’s Latitude Effect…” | Lemaître, Vallarta (1936). “On the Allowed Cone…” |
| 4. Vallarta (1935). “On the Longitude Effect…” | Lemaître, Vallarta (1936). “On the Geomagnetic Analysis…” |
| 5. Lemaître, Vallarta, Bouckaert (1935). “On the North–South…” | Forbush, Gill, Vallarta (1949). “On the Mechanism…” |
| 6. Vallarta (1939). “Present Status of the Theory…” | Lemaître, Vallarta, Bouckaert (1935). “On the North–South…” |
| 7. Vallarta (1938). “An Outline of the Theory…” | Vallarta (1933). “The Interpretation of the Azimuthal Effect…” |
| 8. Vallarta, Graef, Kusaka (1939). “Galactic Rotation…” | Vallarta (1935). “On the Longitude Effect…” |
| 9. Wiener, Vallarta (1929). “On the Spherically Symmetrical…” | Vallarta, Graef, Kusaka (1939). “Galactic Rotation…” |
| 10. Vallarta (1937). “Cosmic Rays and the Magnetic…” | Barajas, Birkhoff, Graef, Vallarta (1944). “On Birkhoff’s…” |
alongside brilliant physicists of the time in the fields of quantum mechanics and relativity. In 1932, Vallarta published his last two papers on these areas and both are outside the central network (Fig. 7b). The largest network represents his final dissertation co-authored with Nathan Rosen, “The Relativistic Thomas–Fermi Atom” is the most cited work to date. It can be interpreted as a paper in which Vallarta and Rosen propose new ideas that deviate from the accumulation of traditional citations. That’s why they are now gaining relevance.

As mentioned earlier, after meeting Compton in Mexico in 1932, Vallarta decided to pursue cosmic rays research. Compton (Nobel Prize winner in 1927) was in controversy with Robert Andrews Millikan, (Nobel Prize winner in 1923) who had a different idea of the origin and composition of cosmic rays. This debate attracted the attention of the international scientific community as well as the general public. Thanks to Vallarta, Lemaître (who knew Millikan and with whom he had discussed his work) decided to step in and they both came up with such important contributions on the matter that their papers were among the most extensively cited ones of that time and even today.

As it can be seen on Fig. 7b and c, Vallarta completed his first field and opened a new one in a remarkable way. Both the last article in the first field and the first one in cosmic rays contain references that are completely different from the ones he used. The last publication in the first area is the most cited, and the first paper on cosmic rays is the second cited so far. This paper is entitled “On Compton’s Latitude Effect of Cosmic Radiation” was co-authored with Lemaître and published in January 1933. This is surprising given that the paper with Rosen had been published a few months earlier in August 1932. These two articles contain new discoveries that are still referenced in the international scientific community.

Figure 8 shows the network of authors that Vallarta cited in his research paper (backward citations). We can see two stages of his scientific trajectory. The network in Fig. 8b shows that during his first stage as researcher, he cited a large number of authors and very little of his own research. He later made his own contribution, this paper was outside the circle of references he had been consulting for years. The Fig. 8a highlights his growth in the field of cosmic rays until 1940, the year in which he stopped publishing for four years and the United States participated in Wold War II. This situation resulted in Vallarta’s successful productivity decay since he could no longer make use of the computer that was directed toward military projects. In Mexico, a developing country, there was no such equipment, it was impossible to buy or construct because the physics and engineering research was beginning. When coming back to Mexico, Vallarta had to seek a different way of doing research. It was not until 1944 that his next paper was published, and the last one in 1962.

The separation between the first and second network (Figs. 7 and 8 respectively) demonstrates that the set of references Vallarta used in his research during the first years of his scientific productivity (without considering the books he cited) was different from the fields in each network. It is worth mentioning that we changed the layout of the network in Fig. 8 with respect to Fig. 7 because the references cited once by Vallarta can only be viewed in the external domain, while references cited multiple times in different works can be seen in the internal area. Later, Table 4 will compare the parameters obtained from the Cytoscape program (3.7.2).

Vallarta published almost two dozen papers on quantum mechanics and hardly cited his own work in almost one decade. On the other hand, he published almost three dozen papers on cosmic rays in almost two decades. Evidently, he dedicated more years to cosmic...
rays. It explains the higher values of network parameters in the field of cosmic rays (see Table 4). Figures 9 and 10 amplify a section of each of the networks in Fig. 8. It is clear that the citation density of the inner region of the cosmic rays network is higher than the citation density of the first field.

Figure 11a represents the citation network both backwards and forwards. The amplification of a region is included to make an approach towards the network structure (Fig. 11b). The node in the network with the most connections is Vallarta’s article with the most citations.

The values for the backward, forward, and total network Cytoscape parameters (undirected) are shown below. The backward network values tend to be higher than the forward ones. This is because the network is larger in its original structure. Its clustering coefficient is non-zero. That means there is an intersection between Vallarta’s works. For example, he self-quoted. The forward network, presents a disconnection between his works, because authors who cited him did not cite each other. The entire network (forward and backward) has different structure and the relationship is not linear. There are even more connections between Vallarta’s papers to the ones in the outer region.

Three different network distribution types can be identified:

i) The Poisson distribution model (or Erdös-Rényi model) characterized by the fact that its nodes are uniformly distributed;

ii) Exponential distribution, produced in networks in which each new node added has the same probability of being linked than the others (equal link); and

iii) Scale-free distribution. The distribution between nodes does not occur equally, which is why Barabasi (2014) referred to it as preferential attachment. The new nodes added to the network will preferentially connect to the already existing nodes through a larger number of connections. This corresponds to Vallarta’s productivity behavior.

Figure 12 shows the distribution of nodes of a network (backward and forward citation together) made of 499 nodes and 727 edges. The degree of the node is plotted on the x-axis on a logarithmic scale and the frequency on the y-axis is also plotted on the logarithmic scale. The in-grade and out-grade of each node of the directed network were added. According to the linear regression analysis performed in the database, the results indicate that there is a scale-free distribution because the distribution can be approximated by a line with a slope between $-1$ and $-2$. To be exact, $y = -1.18x + 1.8$. The highest frequency (that is, the ones that appear the most in the network) is the node of degree 1 and appears 367 times. Nodes of degree 2 appear 48 times. Nodes of degree 3, 16 times. Nodes of degree 4, 12 times, and so on. This behavior corresponds to the scale-free distribution of general knowledge-production. This is in accordance with a knowledge flow network (Valverde et al., 2007).

After Vallarta’s death, the scientific community looked back on some of his papers, the most relevant works in his field of knowledge. Therefore, some of them have been cited to this day. We consider that these are works that touched the frontier of knowledge and may have participated in the construction of a new paradigm.
Table 3  An example of the structure of forward and backward citation database entries

| Node: Vallarta’s articles | Edge: Backward citations | Edge: Forward citations |
|--------------------------|--------------------------|------------------------|
| Vallarta_1924a           | Born-Heisenberg_1923     | LoriN_2022             |
| Vallarta_1924b           | Einstein_1928            | SunW-ZhangK-MeystreP_2021 |
| Rosen-Vallarta_1932a     | Heaviside_1885           | VoskresenskyDN_2021    |
| Vallarta-Rosen_1932b     | Fermi-Rossi_1933        | GosseJC-PhillipsFM_2001 |
| Lemaitre-Vallarta_1933a  | Stormer_1921            | ZieglerJF_1998        |

The complete list of backward citations is presented in the appendix.

Fig. 7  Networks Representing Vallarta's Citations from 1924 to 1930, 1924–1932 and 1924–1933. . (Attribute circle layout network (Cytoscape 3.7.2 program). For achieving a better visualization of the network evolution from 1930 to 1933, in this graph the quote from Bush (1931) was omitted. Here, Vallarta thanks Professor V. Bush and his assistants for the support with the integration of the differential equation, “a machine for the solution of differential equations developed at this Institute by V. Bush”. For this reason, the network belonging to Vallarta-Rosen1932b (the most cited paper) is integrated into the cosmic rays network, as will be seen in the following graph. The Bush article title is “The differential analyzer. A new machine for solving differential equations”) Source: Developed by the authors with data from Mondragón and Barnés (1978)
**Fig. 8** Comparison between Vallarta’s Two Periods of Scientific Productivity According to his Citations. (Circular layout network (Cytoscape 3.7.2 program). The network in Fig. 8a is linked to the network in Fig. 8b only through the article in Bush (1931) as an acknowledgement for having the differential analyzer at his disposal to perform calculations) Source: Developed by the authors with data from Mondragón and Barnés (1978)

| Cytoscape parameter       | Backward | Forward | Total  |
|---------------------------|----------|---------|--------|
| Clustering coefficient    | 0.011    | 0       | 0.093  |
| Network diameter          | 9        | 6       | 11     |
| Characteristic path length| 3.764    | 3.548   | 4.948  |
| Average number of neighbors| 3.075   | 2.198   | 2.902  |
| Number of nodes           | 333      | 192     | 499    |

Some concepts: *Path* is specific case of a walk that does not go through any vertex more than once (they are all different). *Diameter* is the greatest distance between the paths that go from one node to another in the network. *Degree centrality* simply refers to a node’s degree, i.e., the number of sides connecting one node to other nodes. *Betweenness centrality* quantifies the number of times a node is found along the shortest path between two network nodes. *Closeness centrality* measures the node’s average distance in relation to the other network nodes. *Clustering coefficient* is the minimum length between two nodes, a network’s average length, island distribution and size (Aldana, 2011; Acatitla & Urbina, 2017: 16).
Fig. 9 Amplified section from Quantum Mechanics and Relativity network, 1924–1932 and 1944–1945. (Circular layout network (Cytoscape 3.7.2 program)) Source: Developed by the authors with data from Mondragón and Barnés (1978)

Fig. 10 Amplified section from Cosmic Rays network, 1933–1940 and 1947–1962. (Circular layout network (Cytoscape 3.7.2 program)) Source: Developed by the authors with data from Mondragón and Barnés (1978)
Analysis of Vallarta’s Scientific Production Abstracts (1924–1962) Using Tag-Clouds

Data mining techniques are used to analyze information clusters based on a processing methodology (Han et al., 2012; Tan et al., 2005; Zaki & Meira, 2013). One of the most extensively used techniques is Knowledge Discovery in Databases (KDD). Fayyad, Piatetsky-Shapiro and Smyth (1996) KDD consists of five phases: (1) selecting a data set; (2) pre-processing; (3) transforming data; (4) applying data mining methods; and (5) interpreting and evaluating. The data’s qualitative properties enable a differentiation into: structured data, such as a traditional data table in which information has a predefined arrangement; semi-structured data, in which information has a certain structure and is often nested, having differentiated data types; and non-structured data, like texts, videos or images.

In this section, the non-structured data mining methodology was applied to the abstracts of Vallarta’s papers in the book by Mondragón and Barnés (1978). The abstracts became a guide to the concepts used since; in general, they briefly and concisely describe the research formulation and results. They became an important cluster for data mining and discovering new knowledge. The tag-clouds thus produced a visual representation of the list of frequently used words constructed with specific processing criteria.

KDD methodology was used to define this data mining procedure. Algorithms were implemented in order to manipulate data in PHP language and a PostgreSQL data
A management system was used for storing and retrieving information. This system has been tested in other contexts such as the analysis of tweets and journalistic texts (Piña et al. 2018). The methodology can be described as follows:

1. **Selection.** The initial set of data was defined. In this case, the abstracts of 58 papers. They were digitalized from the original source and stored in a database for processing. The length of the abstracts is between 213 and 2446 words with an average length of 1048 words.

2. **Pre-processing.** The texts were subjected to a cleaning process, eliminating punctuation, apostrophes, mathematical formulas, Unicode graphic symbols, and also special and escape characters. All the letters were transformed into lower case and accents, umlauts, and any diacritical marks on the base letter were removed.

3. **Transformation.** A general word count was carried out, ordering the words in descending order of length. As a result, word-frequency pairs were obtained. In this type of analysis, it is commonly observed that the words that occur more frequently are “empty words,” i.e., words such as articles, prepositions, conjunctions, and relative pronouns that by themselves, have no meaning. Nouns were observed to be among the representative words, which are of importance within the context of scientific work.

4. **Method Application.** Based on the ordered list, words were discarded according to a dictionary of “discarded” words, mainly consisting of “empty words” and words that contributed minimum information within the research context. With the first remaining “n” words, a list was constructed in order to form a tag-cloud.

5. **Evaluation.** Once the tag-clouds were completed, the obtained information was interpreted.

Figure 13a shows the global result obtained from the tag-clouds, ordering the 100 most representative words alphabetically. Figure 13b and c shows the results for each field. A word’s size and color visually represent the frequency in which it appeared in the 58 abstracts; for the sake of information, the sub index represents the absolute value of their appearance.

This methodology applied within a specific historical context automatically evidences that Vallarta's main interest focused on cosmic rays throughout the 38 years he devoted to research. With regard to author names, the tag-clouds show that in Vallarta's initial stage as researcher he referred more frequently to the theories of renowned physicists in the field of relativity and quantum mechanics. However, his attention later shifted to developing his own cosmic radiation theory. Figure 14 presents Bigram Tag Cloud analysis.

The Bigram shows two large (length and number) cores of conceptual content. The left corresponds to cosmic rays, and the right corresponds to quantum mechanics and the theory of relativity. Both are integrated by the content of the general theoretical concepts of physics. The pair of isolated concepts mainly corresponds to cosmic rays, as this was his longest-lasting research field. At the top of the chart, the three words "analyzer-differential-Bush" are displayed together. It explains how important the computer was to Vallarta’s research. This was a device that he recognized in his abstracts.

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32 Vallarta published articles in four languages: English, French, German and Spanish. To compile this database in English only, Ramos-Lara translated the French, German and Spanish abstracts into English.
a machine unique in the world. This was a tool that prevented him from continuing his investigation when he returned to Mexico.

6 Conclusions

The mapping tools—bibliometric analysis, network theory (backward and forward citation), and tag-clouds—used in this paper to study Vallarta, demonstrate the number of citations of his work increased significantly over the last decades. Accounting quantum mechanics and relativity papers, as well as cosmic rays papers; our results showed that Vallarta completed his first field and opened a new one in a remarkable way.

Vallarta’s two most cited papers were published in 1932 and 1933, when he was a researcher-professor at MIT, (he was 33) eight years after having completed his PhD and only four years after coming back from studying in Germany. He immediately engaged in topics about the frontiers of physics; reaching out to other fellow scientists, attending international events of great relevance, and publishing papers for important outlets, soon achieving recognition for his contributions. Moshinsky states that Vallarta’s first publications about quantum mechanics appeared a few months after this field emerged (Moshinsky, 1987, 46) so it is worth mentioning his most cited paper corresponds to this subject of study and was published early during his productive activity ("The Relativistic Thomas–Fermi Atom," 1932). Similarly, Vallarta’s second most cited paper corresponds to one of his leading papers on cosmic rays ("On Compton’s Latitude Effect of Cosmic Radiation," 1933). The third most cited one was
Fig. 13 Tag-Clouds of the Abstracts of Vallarta’s Scientific Production. a All the Period from 1924 to 1962. b Cosmic Rays. c Quantum Mechanics and Relativity. Source: Developed by the authors with data from Mondragón and Barnés (1978)

Fig. 14 Bigram Tag-Clouds of the Abstracts of Vallarta’s Scientific Production. Source: Developed by the authors with data from Mondragón and Barnés (1978)
published in 1936, “On the Allowed Cone of Cosmic Radiation”. All three of them came out in *Physical Journal*, one of the most reputed physics journals at the time.

Using network theory to analyze the first and second papers mentioned above, initially they were found to be outside the main network, thus representing a new insight outside the usual discussion. It can be interpreted that’s the reason why they continue to receive the largest number of citations. An interesting result of this work is that “The relativistic Thomas–Fermi atom,” was never cited by Vallarta but his three most currently cited articles on cosmic rays; were the most cited by himself in his own papers. These results showed his achievements breaking through the frontiers of physics.

The network structure confirmed Vallarta’s evident and radical academic turn in 1932 from quantum mechanics and relativity to cosmic rays (in which the specialized literature was entirely new). It showed no intersection between the two domains that literature surpassing the edge of physics knowledge, had done yet. One interesting fact we found is that Vallarta cited a lot of his own papers on cosmic rays, as he was a pioneer in the field, unlike the ones on quantum mechanics and relativity. Tag-cloud analysis indicated he was more interested in cosmic rays, having published a large number of papers in that domain. It also revealed that Einstein and Schrödinger were the scientists he mentioned most often, suggesting that; early in his career, he referenced theories developed by other physicists but soon he began formulating his own theory.

Bigram displays two large cores of conceptual content representing Vallarta’s fields of study. The isolated concepts correspond mainly to cosmic rays, his longest-lasting research field, the words "analyzer-differential-Bush" also appeared showing how important a computer for his research was (only a few worldwide, none in Mexico). Mexican economy made it impossible to purchase such expensive technological equipment. It could not be built because physics and engineering research were just beginning. The three tools also allowed us to visualize how his productivity decayed after 1940, and the years after he came back to Mexico to promote the development of science, technology, and education, as well as becoming a science diplomat and setting aside the scientific production.

Definitely, World War II had an adverse effect on Vallarta’s work, which was then at its peak. The computer equipment necessary for his calculations was redirected to military projects so he lost access to it. This situation might have persuaded him to reconsider returning to the field of relativity, since the first paper that came out when he resumed publication in 1944 focused on this theme and was a collaboration with Barajas, Birkhoff, and Graef. But they never referenced the most cited article today, Vallarta and Rosen (1932).

Finally, the results of the backward and forward network analysis revealed a scale-free distribution confirming that the way in which Vallarta constructed knowledge is parallel to the way knowledge has been constructed throughout history (in accordance with a knowledge flow network). Forward and backward citation presents a power law behavior. His articles featured in the best research journals of the time are the most cited. The interdisciplinary nature of the mapping studies of scientist’s contributions using scientometric tools showed an interaction between economic, political and social elements. Many questions arose from these studies whose answers require the formation of interdisciplinary research teams. Their results can help us understand the process of knowledge production. We are confident that the methodology used in this paper will help mapping the contributions of other scientists.

**Appendix**

See Table 5.
| Program’s tag    | Title of Vallarta’s paper                                                                 |
|-----------------|------------------------------------------------------------------------------------------|
| Vallarta_1924a  | Note on the Quantization of Non-Conditioned Periodic Systems                               |
| Vallarta_1924b  | Notes on Dynamical Systems Non-Integrable by Separation of Variables and on the Existence of “Unmechanical” Orbits in the Atom |
| Vallarta_1925a  | Sommerfeld’s Theory of Fine Structure from the Standpoint of General Relativity           |
| Vallarta_1925b  | Theory of the Continuous X-Ray Spectrum                                                   |
| Vallarta_1926a  | Heaviside’s Proof of His Expansion Theorem                                                |
| Vallarta_1926b  | El Tratamiento del Estado Transitorio de una Línea de Transmisión de Energía Eléctrica por el Método Operacional de Heaviside |
| Vallarta_1926c  | Bermerkung zu der Arbeit von Ludwig Casper “Zur Formel von Heaviside für Einschaltvorgänge” |
| Vallarta_1927a  | On the Conditions of Validity of Macromechanics,                                          |
| Vallarta_1927b  | Sobre la Teoría Relativista de la Mecánica Ondulatoria                                   |
| Vallarta_1927c  | Bermerkungen zu der Arbeit von Herrn G. von Gleich: Zur Massenveränderlichkeit im Zweikörperproblem |
| Wiener-Vallarta_1929a | Unified Field Theory of Electricity and Gravitation                                        |
| Struik-Vallarta_1929b | [Discussion on] Statistical Interpretation of Various Formulations of Quantum Mechanics, |
| Wiener-Vallarta_1929c | On the Spherically Symmetrical Statical Field in Einstein’s Unified Theory of Electricity and Gravitation |
| Vallarta_1929d  | On Einstein’s Unified Field Equations and the Schwarzschild Solution                      |
| Wiener-Vallarta_1929e | On the Spherically Symmetrical Statical Field in Einstein’s Unified Theory: A correction |
| Vallarta_1929f  | Note on the Statistical Interpretation of Maxwell’s Equations                              |
| Vallarta_1930a  | The Unified Field Theory and Schwarzschild’s Solution: A Reply                            |
| Rosen-Vallarta_1930b | The Spherically Symmetrical Field in the Unified Theory                                     |
| Rosen-Vallarta_1932a | Relativity and the Uncertainty Principle                                                  |
| Vallarta-Rosen_1932b | The Relativistic Thomas–Fermi Atom                                                        |
| Lemaitre-Vallarta_1933a | On Compton’s Latitude Effect of Cosmic Radiation                                          |
| Vallarta_1933b  | The Interpretation of the Azimuthal Effect of Cosmic Radiation                             |
| Lemaitre-Vallarta-Bouckaert_1935a | On the North–South Asymmetry of Cosmic Radiation                                           |
| Vallarta_1935b  | On the Longitude Effect of Cosmic Radiation                                                |
| Lemaitre-Vallarta_1936c | Contributions à la théorie des effets de latitude et d’asymétrie des rayons cosmiques – Calcul d’une famille d’orbites asymptotiques |
| Lemaitre-Vallarta_1936a | On the Geomagnetic Analysis of Cosmic Radiation                                            |
| Lemaitre-Vallarta_1936b | On the Allowed Cone of Cosmic Radiation                                                    |
| Vallarta_1937a  | Longitude Effect of Cosmic Radiation and the Position of the Earth’s Magnetic Centre      |
| Vallarta_1937b  | Cosmic Rays and the Magnetic Moment of the Sun                                              |
| Vallarta-Jesse_1937c | Geographic Asymmetries of Cosmic Rays as Related to the Earth’s Magnetization             |
| Vallarta_1938   | An Outline of the Theory of the Allowed Cone of Cosmic Radiation (Vallarta’s book published in Toronto, The University of Toronto Press) |
Table 5 (continued)

| Program’s tag                 | Title of Vallarta’s paper                                                                 |
|-------------------------------|------------------------------------------------------------------------------------------|
| Vallarta_1939a                | Present Status of the Theory of the Effect of the Earth’s Magnetic Field on Cosmic Rays  |
| Vallarta-Graef-Kusaka_1939b   | Galactic Rotation and the Intensity of Cosmic Radiation at the Geomagnetic equator        |
| Vallarta-Feynman_1939c        | The Scattering of Cosmic Rays by the Stars of a Galaxy                                    |
| Vallarta_1939d                | Are There Multiple Charged Primary Particles in Cosmic Radiation?                         |
| Vallarta-Godart_1939e         | A Theory of World-Wide Periodic Variations of the Intensity of Cosmic Radiation           |
| Vallarta_1939f                | The Determination of the Energy Spectrum of Primary Cosmic Radiation                     |
| Vallarta_1940                 | Remarks on Zwicky’s Paper “On the Formation of Clusters of Nebulae and the Cosmological Time Scale” |
| Barajas-Birkhoff-Graef-Vallarta_1944a | On Birkhoff’s New Theory of Gravitation                                                 |
| Vallarta-Perusquia-Oyarzabal_1947a | The Determination of the Sign and the Energy Spectrum of Primary Cosmic Radiation       |
| Vallarta_1947b                | On the Magnetic Field of the Milky Way and Its Effect on Cosmic Radiation                 |
| Vallarta_1948a                | Cosmic Rays and the Magnetic Field of the Moon                                           |
| Vallarta_1948b                | On the Energy of Cosmic Radiation Allowed by the Earth’s Magnetic Field                  |
| Vallarta_1949a                | Sobre el Espectro de Energía de la Radiación Cósmica Primaria y Cálculo de Experimentos de Cohetes Fuera de la Atmósfera |
| Forbush-Gill-Vallarta_1949b   | On the Mechanism of Sudden Increases of Cosmic Radiation Associated with Solar Flares   |
| Vallarta_1949c                | Galactic Rotation Effect and the Origin of Cosmic Radiation                              |
| Vallarta_1949d                | On the Low Energy Spectrum of Primary Cosmic Radiation and the Sun’s Magnetic Dipole Moment |
| Vallarta_1950                 | On the Energy Spectrum of Heavy Nuclei in Primary Cosmic Radiation                       |
| Vallarta-Gall-Lifshitz_1958   | Geomagnetic Coordinates and Cosmic Radiation                                             |
| Vallarta_1961                 | Theory of the Geomagnetic Effects of Cosmic Radiation                                    |
| Vallarta_1962                 | Sobre la Cavidad Formada en el Plasma Solar por el Campo Magnético Terrestre y el Umbral de Energía de la Radiación Cósmica |

The articles without references are not on this list

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References

Acatitla, E., & Urbina, J. (2017). El uso de redes complejas en economía: Alcances y perspectivas. In Inter-disciplina, 5(12), 9–22.
Aldana, M. (2011). Redes complejas: Estructura, dinámica y evolución. México: Retrieved from: http://www.fis.unam.mx.
Baker, A. (2013). Complexity, networks, and non-uniqueness. Foundations of Science, 18, 687–705. https://doi.org/10.1007/s10699-012-9300-0
Barabási, Á. L. (2014). Network science. Graph theory. CC BY-NC-SA 2.0. Retrieved from: https://barabasi.com/f/625.pdf.
Barzel, B., & Barabási, Á. L. (2013). Universality in network dynamics. Nature Physics, 9, 673–681. https://doi.org/10.1038/nphys2741
Bornmann, L., Haunschild, R., & Hug, S. E. (2018). Visualizing the context of citations referencing papers published by Eugene Garfield: A new type of keyword co-occurrence analysis. Scientometrics, 114, 427–437.
Bush, V. (1931). The differential analyser. A new machine for solving differential equations. Journal of the Franklin Institute, 212, 447.
Del Río, F. (2018). Destellos del cosmos. Ensayo biográfico sobre Manuel Sandoval Vallarta. El Colegio Nacional.
Del Río, J. A., Russell, J. M., & Juárez, D. (2020). Applied physics in Mexico: Mining the past to predict the future. Scientometrics, 125, 187–212. https://doi.org/10.1007/s11192-020-03639-7
East, R., & Ang, L. (2021). Insight: The key to faster progress in science. Foundations of Science, 26, 503–514. https://doi.org/10.1007/s10699-020-09692-y
Esqueda-Blas, E., & Ramos-Lara, M. P. (2013). Nabor Carrillo: pionero de la energía nuclear en México. Quipu. Revista Latinoamericana De Historia De Las Ciencias y La Tecnología, 15(3), 285–319.
Fayyad, U., Piatetsky-Shapiro, G., & Smyth, P. (1996). From data mining to knowledge discovery in databases. American Association for Artificial Intelligence, 17(3).
Gall, R. (1987b). Los rayos cósmicos y sus grandes pioneros (pp. 87–96). Manuel Sandoval Vallarta. Hom- enaje. México: Instituto Nacional de Estudios Históricos de la Revolución Mexicana.
Gall, R. (1987a). La teoría de los efectos geomagnéticos en los rayos cósmicos, su pasado y su presente (pp. 59–75). Manuel Sandoval Vallarta. Homenaje. México: Instituto Nacional de Estudios Históricos de la Revolución Mexicana.
Genuth, J. (1987). Groping towards science policy in the United States in the 1930s. Minerva, 25, 238–268. https://doi.org/10.1007/BF01097784
Han, J., Kamber, M., & Pei, J. (2012). Data mining: Concepts and techniques. Morgan Kaufmann.
L’Annunziata, M. F. (2016). Radioactivity: Introduction and history, from the quantum to quarks (2nd ed.). Elsevier.
Lancho-Barrantes, B. S., & Cantú-Ortiz, F. J. (2019). Science in Mexico: A bibliometric analysis. Scientometrics, 118, 499–517. https://doi.org/10.1007/s11192-018-2985-2
Lemaître, G., & Vallarta, M. S. (1933). On Compton’s latitude effect of cosmic radiation. Physical Review, 43, 87.
Mapping Manuel Sandoval Vallarta (1899–1977) Scientific

Leydesdorff, L., Wouters, P., & Bornmann, L. (2016). Professional and citizen bibliometrics: Complementarities and ambivalences in the development and use of indicators—a state-of-the-art report. *Scientometrics, 109*, 2129–2150.

Lotka, A. J. (1926). The frequency distribution of scientific productivity. *Journal of the Washington Academy of Sciences, 16*(12), 317–323.

Lozano, J. M., García-Colín, L., & Calles, A. (1982). Historia de la Sociedad Mexicana de Física. *Revista Mexicana De Física, 28*(3), 277–293.

Mateos, G., & Minor, A. (2013). La red internacional de rayos cósmicos, Manuel Sandoval Vallarta y la física en México. *Revista Mexicana De Física E, 59*, 148–155.

Mendoza, E. (1995). *Semblanza Dr. Manuel Sandoval Vallarta. Exdirector General del Instituto Politécnico Nacional*. México: Instituto Politécnico Nacional.

Mendoza, R. M., Acacita Romero, E., & Urbina Alonso, J. (2019). La importancia de la obra de Arturo Rosenblueth en la ciencia contemporánea: Un análisis bibliométrico. *Arturo Rosenblueth. Legado y vigencia de sus contribuciones* (pp. 373–396). Universidad Nacional Autónoma de México.

Minor, A. (2019). *Cruzar fronteras. Movilizaciones científicas y relaciones interamericanas en la trayectoria de Manuel Sandoval Vallarta (1917–1942)*. México: UNAM-CISAN y El Colegio de Michoacán A. C.

Minor, A., & Vargas, J. (2015). La incursión del Científico diplomático en el siglo XX: Dos experiencias mexicanas. *Revista Digital Universitaria, 16*(4), 1–16.

Mondragón, A. (1987). La obra científica de Manuel Sandoval Vallarta (pp. 13–42). *Manuel Sandoval Vallarta. Homenaje*. México: Instituto Nacional de Estudios Históricos de la Revolución Mexicana.

Mondragón, A. (1999a). Manuel Sandoval Vallarta y la física en México. *Ciencias, 53*, 32–39.

Mondragón, A. (1999b). Manuel Sandoval Vallarta: Iniciador de la física teórica e impulsor de la ciencia en México. *Bol. Soc. Mex. Fís., 13*(3), 109–119.

Mondragón, A., & Barnés, D. (1978). *Obra científica*. Universidad Nacional Autónoma de México.

Moshinsky, M. (1987). Un precursor: Manuel Sandoval Vallarta (pp. 43–75). *Manuel Sandoval Vallarta. Homenaje*. México: Instituto Nacional de Estudios Históricos de la Revolución Mexicana.

Newman, M. E. J. (2010). *Networks: An introduction*. Oxford University Press.

Peritz, B. C., Bar-Ilan J. (2002). The sources used by bibliometrics-scientometrics as reflected in references. *Scientometrics, 54*(2), 269–284.

Piña-García, C. A., Siqueiros-García, J. M., Robles-Belmont, E., et al. (2018). From neuroscience to computer science: A topical approach on Twitter. *J Comput Soc Sc, 1*, 187–208. https://doi.org/10.1007/s42001-017-0002-9

Ramos-Lara, M. P. (2005). De la física ingenieril a la creación de la primera profesión de física en México. *Revista Mexicana De Física E, 51*(2), 137–164.

Ramos-Lara, M. P. (2015). Figuras y entidades pioneras de la física en México. *Revista Mexicana De Física E, 61*, 93–103.

Ramos-Lara, M. P. (2019). Rosenblueth y Sandoval Vallarta, científicos mexicanos de prestigio internacional comprometidos con el desarrollo de la ciencia de frontera en México. *Arturo Rosenblueth. Legado y vigencia de sus contribuciones* (pp. 87–106). Universidad Nacional Autónoma de México.

Rebolledo, J. (1987). *Curriculum vitae* (pp. 157–173). *Homenaje*. México: Instituto Nacional de Estudios Históricos de la Revolución Mexicana.

Riaza, E. (2010). *La historia del comienzo: Georges Lemaître, padre del Big Bang*. Ediciones Encuentro.

Saam, N., & Reiter, L. (1999). Lotka’s Law reconsidered: The evolution of publication and citation distribution of publication and citation distributions in scientific fields. *Scientometrics, 44*(2), 135–155.

Solé, R. (2009). *Redes complejas*. Tusquets.

Tan, P. N., Steinbach, M., & Kumar, V. (2005). *Introduction to data mining*. Pearson/Addison Wesley.

Vallarta, M. S. (1961). Theory of the geomagnetic effects of cosmic radiation. *Encyclopedia of Physics*, Vol. XLVI/1. Springer-Verlag.

Vallarta, M. S. (1938). *An outline of the theory of the allowed cone of cosmic radiation*. University of Toronto Press.

Vallarta, M. S., & Rosen, N. (1932). The relativistic Thomas-Fermi atom. *Physical Review, 41*, 708.

Valverde, S., Solé, R. V., Bedau, M. A., & Packard, N. (2007). Topology and evolution of technology innovation networks. *Physical Review, 76*, 056118.

Zaki, M., & Meira, W. (2013). *Data mining and analysis: Fundamental concepts and algorithms*. The Cambridge University Press.

Zweig, K. (2016). *Network analysis literature. A practical approach to the analysis of networks*. Springer-Nature.
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