A bibliometric study of the work of Rosalind E. Franklin (1920-1958)
Une étude bibliométrique des travaux de Rosalind E. Franklin (1920-1958)

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Article abstract
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Abstract: After a short introduction to her life and work, we construct Rosalind Franklin's citation environment in the sense of Howard White. This environment consists of four groups of authors related to Franklin: her co-authors, those cited by Franklin, those co-cited with Franklin, and those citing Franklin. We further found two of her articles that can be considered as suffering from delayed recognition. The article ends with a complete bibliography of Franklin. Although she never received the Nobel Prize, she most certainly was “of Nobel Class.”

Keywords: double helix, crystallography, citation environment, h-indices, delayed recognition

Introduction

This article has been written on the occasion of the 100th anniversary of the birth of Rosalind Franklin. We do not focus on her life or even her science, but mainly
study her scientific achievements from a bibliometric point of view. We provide, in the
words of Howard White (White 2000, 2001), an ego-centered picture of Franklin. In this
way, we provide a longitudinal study of the acceptance of her ideas, first through
publications and co-authors, and later through citations of her publications. For the
definitions and more information about the used bibliometric notions, we refer the

**Rosalind Franklin: A scientist’s life**

Rosalind Franklin was born on 25 July 1920 in London, England into an influential
British-Jewish family. She died on 16 April 1958, in London.

Franklin made advances in three significant areas: the understanding of coal, the
shape of the DNA (deoxyribonucleic acid) molecule, and the way RNA (ribonucleic acid)
functions inside viruses. She is widely described as a brilliant experimentalist. She
started higher education at Cambridge, from which she graduated in 1941. The British
Coal Utilisation Research Association offered her a war-related research position in
1942, which led her to study the porosity of coal. Through this, she discovered the
relationship between the fine constrictions in the pores of coals and the permeability of
the porous space. From this she was able to classify coals and accurately predict their
performance, for instance in gas masks—a fact recently recalled in *Nature* (2020). This
research led to her Ph.D. in 1945. In 1947 she crossed the Channel and started working
as a postdoctoral researcher in Méring’s Laboratoire Central des Services Chimiques de
l’État (Paris). It is there that she learned to apply X-ray crystallography to amorphous
substances and became an accomplished X-ray crystallographer. Applying these
techniques to coal and similar materials, she proposed the terms *graphitizing and non-
graphitizing carbon* (Franklin 1951).

In 1951 she moved to King’s College in London as a research associate, more
precisely to the Medical Research Council’s Biophysics Unit, directed by John Randall
(Maddox 2002). Franklin, now working with Gosling as her doctoral student, started to
apply her expertise in X-ray diffraction techniques to the structure of DNA. They
discovered that there were two forms of DNA: at high humidity, the DNA fiber became
long and thin; when it was dried it became short and fat (Maddox 2002). Franklin
named these two forms "B" and "A" respectively (Klug 1968). In this way, Franklin and
Gosling became very close to the solution of finding the structure of DNA. In fact, it was
their X-ray diffraction data that put Watson and Crick on the way to the ultimate
solution—actually of the B form—for the structure of DNA, and a Nobel Prize in 1962.
Owing to disagreements with John Randall and more so with Maurice Wilkins (who
shared the Nobel Prize in 1962), Franklin moved to Birkbeck College (London) in 1953.

There she started exploring RNA and worked with Aaron Klug, who had just
earned his Ph.D. degree. Again, she used her skills as an X-ray crystallographer to study
the structure of the tobacco mosaic virus, an RNA virus. On the suggestion of
colleagues from Berkeley (California), she expanded her interests from plant viruses to
animal viruses, in particular the poliovirus. After Franklin died in 1958, Klug succeeded
her as a group leader, and he, Finch, and Holmes continued investigating the structure
of the poliovirus. Klug received the Nobel Prize in Chemistry in 1982 for “the structural elucidation of biologically important nucleic acid-protein complexes.” Few doubt that if Rosalind Franklin had still been alive, she would have shared this Nobel Prize.

From this short overview of her work, we see that Franklin’s research focused on three topics, moving from one to the other over time. At first, she worked with coal and carbonaceous material, then moved to diffraction studies of DNA and its structure, and finally, she started to study plant and animal viruses. For a full description of her life, we refer the reader to the book written by Brenda Maddox (Maddox 2002), and for a precise account of her role in the discovery of the structure of DNA we refer to the article written by Klug, Franklin’s closest colleague at Birkbeck College, who inherited her notebooks (Klug 1968).

Franklin’s obituary was written by John Desmond Bernal (Bernal 1958), her director at Birkbeck College. Bernal was not only a crystallographer and molecular biologist, but also one of the founders of the science of science through his work on the sociology of science (Bernal 1939). Franklin received posthumous recognition in many ways. In 2020 the Royal Mint minted a 50 pence coin in her honor. Moreover, several buildings and institutes are named after her.

Franklin’s work seen through a bibliometric lens

Franklin published 55 documents, including her doctoral thesis and some short abstracts (see Appendix). Note that all counts of publications and citations provided in this article are complete or normal counts. These documents are spread over a period of 15 years: 1945-1959. Seven are published during the first 5 years, 20 during the second period, and 28 during the last. This shows that her scientific work was still increasing when she died prematurely. Of these 55 publications, 34 are classified as articles, 12 as (meeting) abstracts, 5 as notes, 2 as letters, one as editorial material, plus her doctoral thesis. These publications are mainly written in English, but seven are published in other languages: mainly French and German. One abstract is even written in Serbian. Her yearly publication h-index is 5 (Mahbuba and Rousseau 2013). This means that there are five years during which she published 5 or more documents: 1953 (8 publications), 1957 (7 publications), 1958 (7 publications), 1956 (6 publications), and 1955 (5 publications).

Nowadays (circa 2020) her (standard) h-index is 23. This h-index increased over the years in the way shown in Figure 1.
One can see that this increase is largely linear till approximately 1965 (already 7 years after her death). From then on, her h-index slowly reached a plateau. In this case, the h-index increased linearly, at least during her life, as assumed by Hirsch, when introducing the m-quotient (Hirsch 2005). The h-core includes about two-thirds of her (normal) articles, say citable documents.

Next, we have a look at her most-cited articles according to the Web of Science (WoS). These are shown in Table 1.

<table>
<thead>
<tr>
<th>Citation</th>
<th>Times cited</th>
</tr>
</thead>
</table>

Table 1: The five most-cited articles written by Rosalind Franklin (from WoS as of December 2020)

Remarkably, this list includes mainly her earlier work. No article from her Birkbeck period is included. The reason for this is probably the fact that she started a new line of inquiry, finished by Klug and his colleagues after her premature death (getting him a Nobel Prize). The second article in Table 1 is the one published in Nature, together with the famous Watson-Crick article (Watson and Crick 1953). As published, it was considered to be supporting evidence for the Watson-Crick one.

We note that among Franklin’s publications, meeting abstracts are not or rarely cited, see Appendix for the exact numbers. This corresponds with the observations made in Hu and Rousseau (2013). Her research was mainly published in the following journals: Acta Crystallographica (7 articles and 7 other contributions), Nature (7+2), Biochimica et Biophysica Acta (4+3), and the Transactions of the Faraday Society (3+3).

Franklin’s citation environment

By the term “citation environment’ we follow White’s schema consisting of four groups of authors related to the author under investigation (the ego) (White 2000, 2001). These are: the co-authors, those providing the ego’s citation identity (the ego’s citees), the citation image (the ego’s co-citees), and the citation image makers (citing the ego).

Co-authors

Beginning with the co-authors, we found 14 different co-authors. The most important ones are shown in Table 2.

<table>
<thead>
<tr>
<th>Co-author</th>
<th>In articles (including edited books)</th>
<th>In other publications</th>
<th>Relation to Franklin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klug, A.</td>
<td>9</td>
<td>3</td>
<td>Started as a post-doc at Birkbeck College; co-worker</td>
</tr>
<tr>
<td>Gosling, R. G.</td>
<td>5</td>
<td>2</td>
<td>Research student at King’s College London</td>
</tr>
<tr>
<td>Holmes, K. C.</td>
<td>4</td>
<td>1</td>
<td>Colleague at Birkbeck College</td>
</tr>
<tr>
<td>Finch, J. T.</td>
<td>3</td>
<td>0</td>
<td>Research student at Birkbeck College, hired by Franklin</td>
</tr>
</tbody>
</table>

Table 2: Franklin’s most-important co-authors

Citees

Next, we come to Franklin’s citation identity: this is the set of authors cited at least once by the ego. For this, we need the complete reference lists of all Franklin’s
publications. This was easy for those publications included in the Web of Science. We tried to collect all other publications to read their reference lists. Unfortunately, we could not find two abstracts. As abstracts by Franklin usually have no reference list, the data in the next tables are almost certainly not influenced by this gap. Unsurprisingly, she cited herself the most. When an author is cited more than once in one of Franklin’s reference lists this is counted as often as there are different publications by this author cited.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Times referenced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Franklin, R.E.</td>
<td>100</td>
</tr>
<tr>
<td>Schramm, G.</td>
<td>38</td>
</tr>
<tr>
<td>Bernal, J. D.</td>
<td>24</td>
</tr>
<tr>
<td>Watson, J. D.</td>
<td>23</td>
</tr>
<tr>
<td>Crick, F. H. C.</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 3: Top five scientists cited the most in Franklin’s publications (her citation identity)

Table 4 shows the articles that are most cited by Franklin. These refer to her research on viruses. Note that it was not unusual at that time to read and refer to articles written in German.

<table>
<thead>
<tr>
<th>Publications</th>
<th>Times used</th>
</tr>
</thead>
</table>

Table 4: Top five most-used articles

**Co-citees**

Now we determine the authors most-cited together with Franklin. According to the WoS, the following 8 authors are each co-cited at least 750 times with Franklin: Watson, J. D. (1,573 times), Wilkins, M. H. F. (940 times), Schramm, G. (819 times),
Oberlin, A. (814 times), Pauling, L. (785 times), Klug (770 times), Fraenkel-Conrat (762 times) and Crick (761 times). This ego author co-citation network is shown in Figure 2 using VOSviewer (van Eck and Waltman, 2010, 2014).

Following on from the author co-citation map we show Franklin’s article co-citation map (Figure 3) also constructed through VOSviewer (van Eck and Waltman 2010, 2014). We set the minimum number of citations of a cited reference as 20; 317 articles meet this threshold. In Figure 3, a node represents a document. Its size indicates its citation frequency. The thickness of a line between two nodes (a link in the network) represents the number of co-citations of the two documents. In Figure 3, only lines for co-citation counts greater than or equal to 5 are shown. Figure 3 clearly shows the three research interests of Franklin: coal and carbonaceous material (left), diffraction studies of DNA (upper right), and viruses (lower right).

Figure 2: Author co-citation map of Rosalind Franklin
Citing Franklin (the ego): The citation image makers

Franklin received more than 11,500 citations in the Web of Science. By this, we mean that there are 11,500 citation instances, where an article with five authors citing at least one article by Franklin counts for five citation instances.

The authors with the most articles (in the Web of Science) citing at least one article by Franklin are shown in Table 5. Note that we count articles citing Franklin at least once. Nationality refers to the country in which this scientist worked, not the country of birth. Aaron Klug, for instance, was born in Lithuania, educated in South Africa, but did his important work in England (UK). Gerald Stubbs, who finished the research line on fiber diffraction analysis of tobacco mosaic viruses started by Franklin, was born in Australia and worked for many years in Germany before moving to the USA. The last column of Table 5 mentioned the first year in which this scientist cited Franklin, according to the WoS. Of course, Rosalind Franklin features among the scientists citing her work.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Author</th>
<th>Nationality</th>
<th>No. times citing</th>
<th>First year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Klug, Aaron</td>
<td>UK</td>
<td>33</td>
<td>1955</td>
</tr>
<tr>
<td>2</td>
<td>Stubbs, Gerald</td>
<td>USA</td>
<td>32</td>
<td>1974</td>
</tr>
<tr>
<td>3</td>
<td>Oberlin, Agnes</td>
<td>France</td>
<td>31</td>
<td>1967</td>
</tr>
<tr>
<td>4</td>
<td>Franklin, R. E.</td>
<td>UK</td>
<td>27</td>
<td>1949</td>
</tr>
<tr>
<td>5</td>
<td>Rouzaud, Jean-Noel</td>
<td>France</td>
<td>24</td>
<td>1982</td>
</tr>
<tr>
<td>6</td>
<td>Rupprecht, Allan</td>
<td>Sweden</td>
<td>23</td>
<td>1970</td>
</tr>
<tr>
<td>7</td>
<td>Walker Jr., P. L.</td>
<td>USA</td>
<td>20</td>
<td>1953</td>
</tr>
<tr>
<td>8</td>
<td>Finch, John T.</td>
<td>UK</td>
<td>19</td>
<td>1957</td>
</tr>
<tr>
<td>9</td>
<td>Holmes, Kenneth C.</td>
<td>UK</td>
<td>19</td>
<td>1956</td>
</tr>
</tbody>
</table>
Delayed recognition

We proposed (Rousseau 2018) the following method and definition of an article suffering from delayed recognition, also known as a *sleeping beauty* (van Raan 2004) or *hibernator* (Hu et al. 2018). The three parts: delayed, recognition, and the actual value are operationalized as follows. For the delayed part, we started studying citations ten years after their publication. "Recognition" is operationalized as belonging to the top 1% most-cited publications (at the moment of the investigation, denoted as T) among all WoS publications published in the same year as the target publication. Finally, a fuzzy membership function is determined (Rousseau 2018), based on ideas from Ke et al. (2015), and Du and Wu (2018). This membership function, as calculated at time $T$, is denoted as $DR(T)$, and defined as:

$$DR(T) = \max_{10 \leq t \leq T} \{0, K(t)\}$$  \hspace{1cm} (1)

Here $t$ denotes time since publication and $K(t)$ is defined as

$$K(t) = \frac{2}{(t-1)C(t)} S(t)$$  \hspace{1cm} (2)

where $C(t)$ is equal to the cumulative number of received citations at the beginning of the year $t$, and

$$S(t) = \sum_{n=0}^{t} \left( \frac{C(t)}{t} n - C(n) \right)$$  \hspace{1cm} (3)

The resulting membership value is always situated between 0 and 1. As an ad hoc threshold, we suggested the value 0.333, obtained for linear growth in citations. For more details, we refer the reader to Rousseau (2018). Taking all this into account we found that Franklin's two most-cited articles (noted in Table 6 and Table 7) can be considered to be hibernators. Among these two we have her *Nature* paper published alongside the Watson-Crick one. That this paper suffered delayed recognition is not surprising given the fact that even the Watson-Crick paper was not an immediate success, see further. Figures 4 and 5 illustrate the fact that these two papers suffered from delayed recognition.

<table>
<thead>
<tr>
<th>Year $t$</th>
<th>$K(t)$</th>
<th>Year $t$</th>
<th>$K(t)$</th>
<th>Year $t$</th>
<th>$K(t)$</th>
<th>Year $t$</th>
<th>$K(t)$</th>
<th>Year $t$</th>
<th>$K(t)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1951</td>
<td>0.000</td>
<td>1965</td>
<td>0.054</td>
<td>1979</td>
<td>0.141</td>
<td>1993</td>
<td>0.126</td>
<td>2007</td>
<td>0.245</td>
</tr>
<tr>
<td>1952</td>
<td>0.000</td>
<td>1966</td>
<td>0.067</td>
<td>1980</td>
<td>0.106</td>
<td>1994</td>
<td>0.140</td>
<td>2008</td>
<td>0.265</td>
</tr>
<tr>
<td>1953</td>
<td>0.000</td>
<td>1967</td>
<td>0.090</td>
<td>1981</td>
<td>0.113</td>
<td>1995</td>
<td>0.157</td>
<td>2009</td>
<td>0.278</td>
</tr>
<tr>
<td>1954</td>
<td>0.250</td>
<td>1968</td>
<td>0.130</td>
<td>1982</td>
<td>0.128</td>
<td>1996</td>
<td>0.169</td>
<td>2010</td>
<td>0.295</td>
</tr>
<tr>
<td>1955</td>
<td>0.000</td>
<td>1969</td>
<td>0.225</td>
<td>1983</td>
<td>0.122</td>
<td>1997</td>
<td>0.195</td>
<td>2011</td>
<td>0.300</td>
</tr>
<tr>
<td>1956</td>
<td>0.028</td>
<td>1970</td>
<td>0.252</td>
<td>1984</td>
<td>0.111</td>
<td>1998</td>
<td>0.193</td>
<td>2012</td>
<td>0.314</td>
</tr>
<tr>
<td>1957</td>
<td>-0.116</td>
<td>1971</td>
<td>0.261</td>
<td>1985</td>
<td>0.102</td>
<td>1999</td>
<td>0.214</td>
<td>2013</td>
<td>0.322</td>
</tr>
</tbody>
</table>
Table 6: K-values, formula (2), for Franklin, R. E. (1951). Crystallite Growth in Graphitizing and Non-graphitizing Carbons

<table>
<thead>
<tr>
<th>Year</th>
<th>K(t)</th>
<th>Year</th>
<th>K(t)</th>
<th>Year</th>
<th>K(t)</th>
<th>Year</th>
<th>K(t)</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1953</td>
<td>0.000</td>
<td>1970</td>
<td>-0.156</td>
<td>1987</td>
<td>-0.177</td>
<td>2004</td>
<td>0.123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1954</td>
<td>0.000</td>
<td>1971</td>
<td>-0.175</td>
<td>1988</td>
<td>-0.166</td>
<td>2005</td>
<td>0.154</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1955</td>
<td>0.040</td>
<td>1972</td>
<td>-0.204</td>
<td>1989</td>
<td>-0.124</td>
<td>2006</td>
<td>0.160</td>
<td></td>
<td></td>
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<tr>
<td>1956</td>
<td>-0.063</td>
<td>1973</td>
<td>-0.179</td>
<td>1990</td>
<td>-0.132</td>
<td>2007</td>
<td>0.187</td>
<td></td>
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<tr>
<td>1957</td>
<td>-0.135</td>
<td>1974</td>
<td>-0.168</td>
<td>1991</td>
<td>-0.124</td>
<td>2008</td>
<td>0.232</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1958</td>
<td>-0.183</td>
<td>1975</td>
<td>-0.193</td>
<td>1992</td>
<td>-0.110</td>
<td>2009</td>
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<tr>
<td>1959</td>
<td>-0.174</td>
<td>1976</td>
<td>-0.192</td>
<td>1993</td>
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<td>2010</td>
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<tr>
<td>1960</td>
<td>-0.211</td>
<td>1977</td>
<td>-0.225</td>
<td>1994</td>
<td>-0.068</td>
<td>2011</td>
<td>0.296</td>
<td></td>
<td></td>
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<tr>
<td>1961</td>
<td>-0.143</td>
<td>1978</td>
<td>-0.231</td>
<td>1995</td>
<td>-0.041</td>
<td>2012</td>
<td>0.322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1962</td>
<td>-0.194</td>
<td>1979</td>
<td>-0.237</td>
<td>1996</td>
<td>-0.029</td>
<td>2013</td>
<td>0.349</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1963</td>
<td>-0.171</td>
<td>1980</td>
<td>-0.241</td>
<td>1997</td>
<td>-0.023</td>
<td>2014</td>
<td>0.361</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1964</td>
<td>-0.225</td>
<td>1981</td>
<td>-0.223</td>
<td>1998</td>
<td>-0.008</td>
<td>2015</td>
<td>0.386</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1965</td>
<td>-0.248</td>
<td>1982</td>
<td>-0.197</td>
<td>1999</td>
<td>-0.004</td>
<td>2016</td>
<td>0.406</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4: Cumulative citation curve of Franklin, R. E. (1951) and recognition line
Table 7: K-values, formula (2), for (Franklin and Gosling 1953). Molecular Configuration in Sodium Thymonucleate

<table>
<thead>
<tr>
<th>Year</th>
<th>K-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966</td>
<td>-0.178</td>
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<tr>
<td>1967</td>
<td>-0.186</td>
</tr>
<tr>
<td>1968</td>
<td>-0.148</td>
</tr>
<tr>
<td>1969</td>
<td>-0.118</td>
</tr>
<tr>
<td>1983</td>
<td>-0.165</td>
</tr>
<tr>
<td>1984</td>
<td>-0.154</td>
</tr>
<tr>
<td>1985</td>
<td>-0.154</td>
</tr>
<tr>
<td>1986</td>
<td>-0.153</td>
</tr>
<tr>
<td>2000</td>
<td>-0.010</td>
</tr>
<tr>
<td>2001</td>
<td>-0.001</td>
</tr>
<tr>
<td>2002</td>
<td>0.011</td>
</tr>
<tr>
<td>2003</td>
<td>0.098</td>
</tr>
<tr>
<td>2017</td>
<td>0.418</td>
</tr>
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<td>0.424</td>
</tr>
<tr>
<td>2019</td>
<td>0.438</td>
</tr>
<tr>
<td>2020</td>
<td>0.435</td>
</tr>
</tbody>
</table>

Figure 5: Cumulative citation curve of (Franklin and Gosling 1953), and recognition line

Some remarks

In this section, we provide some extra information related to Franklin’s publications. When using complete-normalized fractional counting (giving each contributing author a score of 1/n when there are n authors in total), Franklin has 37.33 publications, namely 20.83 articles (in journals or edited books) and 16.5 other ones. As Franklin often published on her own, or at most with three co-authors, this reduction in publications (from 55 to 37.22) is much smaller than for most currently active researchers. Franklin published 16 articles with at least 16 references (and not 17). This means that her reference h-index is 16 (Liang and Rousseau 2010).

Conclusion

On the occasion of the 50th anniversary of the famous Watson-Crick article (Watson and Crick 1953) the journal *Nature* published a series of articles related to this
discovery. In this issue, it was observed that the discovery of the double helix structure took some time before it was recognized as essential in the study of heredity. Its reception among scientists was rather lukewarm. Consequently, during the 1950s, the article was rarely cited in *Nature* (Olby 2003). This author noted that the DNA double helix was not taken seriously until a mechanism for its involvement in protein synthesis began to take shape. In another article in this same series Helen Pearson (Pearson 2003) quotes Gasser and other scientists stating that the double helix is not a static structure but that it regularly morphs itself into alternative shapes and structures such as a propeller shape, and other so-called G-quadruplex structures.

Franklin’s publication list and her article co-citation network show her main research interests. Chronologically they are coal and carbonaceous material, diffraction studies of DNA and viruses. The frequency and patterns of citations vary by research topic.

Although she never received the Nobel Prize, Rosalind Franklin most certainly was “of Nobel Class” (Garfield 1987).

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https://doi.org/10.1038/182154a0


http://doi.org/10.1007/s11192-018-2780-0


Appendix: A complete bibliography of Rosalind Elsie Franklin (1920-1959)

All citations were collected in the WoS in October 2020. We added the type of publication and the number of citations to the bibliographical data. The last articles in the list were published posthumously.

1945

1946

1948

1949

1950

1951

1953


1954


1955


1956


1958


**1959**


Moreover, we found the following items related to Rosalind Franklin. For reasons mentioned below, we do not consider them as part of her bibliography.

"Early work on Tobacco Mosaic Virus." 1958. Contribution in the Session on Viruses and Nucleic Acids at the Annual Autumn Conference of the X-ray Analysis Group of the Institute of Physics held in London on 16 and 17 November 1956. *British Journal of Applied Physics* 9: 1-12. This is a report of a meeting in which her contribution is mentioned.