Research Paper

A Bibliometric Framework for Identifying "Princes" Who Wake up the "Sleeping Beauty" in Challenge-type Scientific Discoveries

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Abstract

Purpose: This paper develops and validates a bibliometric framework for identifying the "princes" (PR) who wake up the "sleeping beauty" (SB) in challenge-type scientific discoveries, so as to figure out the awakening mechanisms, and promote potentially valuable but not readily accepted innovative research. (A PR is a research study.)

Design/methodology/approach: We propose that PR candidates must meet the following four criteria: (1) be published near the time when the SB began to attract a lot of citations; (2) be highly cited papers themselves; (3) receive a substantial number of co-citations with the SB; and (4) within the challenge-type discoveries which contradict established theories, the "pulling effect" of the PR on the SB must be strong. We test the usefulness of the bibliometric framework through a case study of a key publication by the 2014 chemistry Nobel laureate Stefan W. Hell, who negated Ernst Abbe's diffraction limit theory, one of the most prominent paradigms in the natural sciences.

Findings: The first-ranked candidate PR article identified by the bibliometric framework is in line with historical facts. An SB may need one or more PRs and even "retinues" to be "awakened." Documents with potential awakening functionality tend to be published in prestigious multidisciplinary journals with higher impact and wider scope than the journals publishing SBs.

Research limitations: The above framework is only applicable to transformative innovations, and the conclusions are drawn from the analysis of one typical SB and her awakening process. Therefore the generality of our work might be limited.

Practical implications: Publications belonging to so-called transformative research, even when less frequently cited, should be given special attention as early as possible, because they may suddenly attract many citations after a period of sleep, as reflected in our case study.

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Originality/value: The definition of PR(s) as the first paper(s) that cited the SB article (self-citing excluded) has its limitations. Instead, the SB-PR co-citations should be given priority in current environment of scholarly communication. Since the "premature" or "transformative" breakthroughs in the challenge-type SB documents are either beyond the current knowledge domain, or violate established paradigms, people's psychological distance from the SB is larger than that from the PR, which explains why the annual citations of the PR are usually higher than those of the SB, especially prior to or during the SB's citation boom period.

Keywords Citation history; Delayed recognition; Awakening mechanisms; Transformative innovation; Nobel Prize

1 Introduction

As early as in the 1960s, some scholars noted the phenomenon that quite a few major scientific discoveries went unnoticed for a long time before they were discovered or rediscovered, and hence were referred to as "resisted discoveries" (Barber, 1961; Cole, 1970), "premature discoveries" (Stent, 1972), or "delayed recognition" studies (Garfield, 1970, 1989, 1990). Studies in this period were mostly case studies from the viewpoint of the sociology of science, and thus gave no quantitative definition about how abrupt a citation boost must be to suggest delayed recognition (Garfield, 1980).

The quantitative concept of "delayed recognition," i.e. "sleeping beauties" (SBs) in science, was proposed by van Raan (2004), who defined SB as a publication that goes unnoticed ("sleeps") for a long time and then, suddenly, attracts a lot of attention ("is awakened by a prince"). He suggested three criteria for distinguishing SBs: (1) deeply asleep (receive at most 1 citation per year on average), or less deeply asleep (between 1 and 2 citations per year on average) for a few years after publication; (2) sleep at least five years; and (3) awakened by over 20 citations during the four years following the sleeping period. Since van Raan's article, scientometrics interest in sleeping beauties has increased considerably.

Recent studies focus on estimating the frequency of occurrence of delayed recognition measured by citation analysis and a few shared features (Glänzel & Garfield, 2004; Glänzel, Schlemmer, & Thijs, 2003); SBs in a specific journal (Kozak, 2013) and in specific subject categories, such as in psychology (Lange, 2005), physics (Marx, 2014; Redner, 2005), mathematics (van Calster, 2012), and medical sciences (Gorry & Ragouet, 2015; Ohba & Nakao, 2012); the awakening probability of SBs based on a well-known stochastic model (Burrell, 2005) or the citation distribution within the sleeping period (Li et al., 2014); the citation lifecycle of SBs (Lachance & Larivière, 2014); a new type of SB with a short leap immediately after publication (Li, 2014; Li & Ye, 2012); the application-oriented tendency of the SBs in physical and engineering sciences (van Raan, 2015). All the above studies identified SBs in terms of average-based criteria directly or indirectly referring to van Raan's definitions.

Different from average-based criteria, Costas, van Leeuwen, and van Raan (2010) used quartile-based criteria, in which papers with delayed recognition are those that have not received 50% of their citations when 75% of other documents in their fields have already received 50% of their citations. These studies concluded that potential cases of delayed recognition are rare in general, and thus have almost no effect on research evaluations for both individual scientists and research groups (Costas, van Leeuwen, & van Raan, 2011, 2013).

Subsequent developments are the redefinition of SBs by referring to average criteria, quartile criteria, and the "boost factor" of citations (Mazloumian et al., 2011). The new method is especially suitable for distinguishing exponential SB citation curves (Li & Shi, 2015). Sun, Min, and Li (2015) proposed a vector for measuring obsolescence of scientific articles. It is designed as $O = (Gs, A\text{-}, n)$, where n is the age of an article, and Gs and A- are parameters for revealing the shape of citation curves. The obsolescence vector yielded more reasonable classifications than did the average-based and quartile-based criteria. Nevertheless, the number of SBs identified is heavily dependent on the adopted rules, which are based on arbitrary threshold parameters for sleeping time and citations.

Previous studies all resulted in the conclusion that SBs are rare and exceptional events in science. To overcome these limitations, Ke et al. (2015) introduced a parameter-free approach, i.e. a "beauty coefficient," to quantify the extent to which a given paper can be considered an SB. The beauty coefficient value B for a given paper is based on a comparison between its citation history and a reference line that is determined by its publication year, the maximum number of citations received in a year, and the year when such maximum is achieved. Their results revealed that the fraction of SBs may be well within 6.5% of all papers indexed in Web of Science. They concluded that the SB phenomenon is far less exceptional than previously thought. Yet this approach fails to cover the citation curve after the paper receives its maximum annual citations (Du & Wu, 2015). The average-based, quartile-based and parameter-free criteria have both advantages and disadvantages in defining and identifying SBs in science, and no consensus about precise definitions of an SB and related concepts has been reached by the scientometric community.

Every sleeping beauty has her prince(s), PR for short, who wakes up the SB by citing the SB document. Following the PR's example, other scientists begin to cite the SB more frequently. There are two kinds of understandings to the identification of the PRs. The first argument focuses on the direct citation relationship between SB and PR, i.e., the PR must cite the SB. According to van Raan (2004), the PR is the first paper to quote the SB (self-citing excluded) before a "citation boom." Braun, Glänzel, and Schubert (2010) sought the candidate PR articles among those that first cited the SB article. Such candidates were supposed to be highly or at least fairly-well cited and to have a considerable number of co-citations with the SB. The second viewpoint emphasizes co-citations between the SB and the PRs by subsequent scholars. Ohba and Nakao (2012) scanned the reference list of articles citing the SB and searched for PRs that were published around the time of the SB's awakening, which prompted the authors of subsequent related works to refer to the SB.

The strength of co-citations was determined by the frequency with which the SB-PR pair is cited together in reference lists. Articles with a co-citation frequency of more than 30% were regarded as PRs for the SB. Li et al. (2014) claimed that the PR is not necessarily the first article that cited the SB. Instead, the PR may just have cited the SB earlier, and—more importantly—caused the SB to receive wide attention and thus awaken. The PRs and the SB are supposed to have a high co-occurrence in the citation network of the SB. For finding the true PRs objectively, they recommended to analyze not only direct citations to the SB, but also consider indirect citations, including using the SB's viewpoint without explaining the original paper, citing knowledge of the SB but not indexing it in references, and so on.

New discoveries and theories are crucial for the development of science, but they are often initially resisted or neglected, and encounter skepticism from the scientific community (Campanario, 2009; Fang, 2014). So the mechanism underlying delayed recognition is always relevant to major scientific progress or groundbreaking scientific revolutions.

Daniel E. Koshland, a former *Science* editor-in-chief, proposed the "cha-cha-cha" typology of scientific discoveries (Koshland, 2007). "*Challenge*" discoveries are a response to an accumulation of facts or concepts that remained unexplained by, or were incongruous with, scientific theories of the time; "*Chance*" discoveries suddenly appear and are often referred to as serendipitous or "unsought findings"; "*Charge*" discoveries solve known problems within an existing theoretical framework which can be considered. According to Kuhn's "paradigm" (Kuhn, 1962), "c*harge*" and "c*hallenge*" discoveries relate to two types of innovative research, cumulative processes and revolutionary breakthroughs, respectively. Koshland's "cha-cha-cha" theory was explained to the informetric community in Rousseau (2007).

It is important to avoid delayed recognition and to detect SBs as early as possible, in order to promote potentially valuable but not readily accepted innovative research.

To accomplish this goal, it is imperative to find the PRs who awaken SBs and figure out why this happens. However, finding the true PR article is a difficult task. In this paper we propose a set of criteria for discerning papers as PRs who brought c*hallenge*-type SBs to the attention of the scientific community. In the next section, we will describe a framework for identifying PRs who woke up SBs, and validate the criteria in terms of a case study of a landmark paper on super-resolved fluorescence microscopy.

2 Framework and Methodologies

Currently, there are two approaches to studying the relationship between SBs and candidate PRs. One argues that the PR is the SB's first citing document; the other claims that the SB and the PR have substantial co-citations, without considering whether the PR directly cited the SB.

We consider the definition of the PR as the first paper that cited the SB suitable only for the very rare cases of "coma sleep", i.e. there is no attention at all in terms of citations, as acknowledged in van Raan (2015). Instead, the SB-PR co-citation relationship should be given priority in finding the PR(s), based on the following considerations.

First, compared with the 19^{th} and 20^{th} centuries, and especially since the introduction of the Internet, the SBs who are sleeping are rarely uncited. Rather, they tend to be cited sporadically by a few publications, including some self-citations.

Second, an alarming trend has been noted towards the citation of review articles rather than the primary research papers in which the original findings were described (Knottnerus & Knottnerus, 2009; Marks et al., 2013). It seems that busy authors do not cite the original work but more recent and perhaps derivative work and reviews. Such behavior renders the papers "cited but not read." Moreover, as the number of papers rises inexorably, authors often have to make a choice about what to cite, and ideas persisting in authors' minds may not be included in the bibliography. Such papers are "read but not cited" (Florence, 2015). The San Francisco Declaration on Research Assessment (DORA) recommends that researchers "wherever appropriate, cite primary literature in which observations are first reported, rather than reviews, in order to give credit where credit is due."[①]

Third, the "real" awakening of the SB is often not a "one PR only" action; hence, observing only the first citation is a limited view.

In order to discover the PRs who wake up SBs, we propose that candidates for being a PR meet the following four criteria:

① http://www.ascb.org/dora/

- Be published near the year in which the SB began to attract a lot of citations;
- Be highly cited papers themselves;
- Receive many co-citations with the SB; and
- Within the *challenge*-type discoveries, PRs' "pulling effect" on the SB should be strong; i.e. the annual number of citations of PRs should be higher than that of the SB, at least during a certain period—namely when the annual citations of the SB begin to increase significantly.

The first three criteria are easy to understand, and are in accordance with previous viewpoints (Braun, Glänzel, & Schubert, 2010; Ohba & Nakao, 2012). Recently developed construal-level theory (Trope & Liberman, 2010) explains the mechanism of people appraising the value of an object through psychological distance. It has been found that if an object is far from one's experiences, he/she will form more abstract representations, or higher level construal, of the object (Liberman et al., 2007). In other words, people are at a large psychological distance from an unfamiliar object.

Novelty and creativity, which have close relationships with scientific discovery, have been shown to be related to high-level construals (Förster, Friedman, & Liberman, 2004). Consequently, people will always estimate a lower probability than the actual value to novelty and creativity in science. Since breakthroughs proposed by an SB are always ahead of their time and outside of the current scope of knowledge, or even violate previous theories, the scientific community may not know of their existence, or dare not to cite the SB, as the new idea has not been observed experimentally, or evidence about the new theory has not been reported. Once the PR occurred, the scientific community discovered and understood the SB because the PR re-introduced or explained the new idea, and thus provided clues for people to know about it. The scientific community then began to cite the SB publication in their work because they were assured now that the work of the SB is correct.

People are at a larger psychological distance from the SB than from the PR. So, at the moment before the SB's citation boom, the number of annual citations of the PR is larger than that of the SB. The PR and the SB are either concept-related or citation-related. In fact, this criterion is also suitable for cases in which the SB is uncited during the sleeping period. In the next section, we will test the usefulness of our bibliometric framework through a key publication of the 2014 chemistry Nobel laureate Stefan W. Hell, who is credited with breaking Ernst Abbe's diffraction resolution limit in fluorescence microscope, although Abbe's theory was one of the most prominent paradigms in the natural sciences.

3 Case Study of Stefan W. Hell's Landmark Work

3.1 Scientific History

The 2014 Nobel Prize in Chemistry was awarded to Stefan W. Hell, Eric Betzig, and William E. Moerner for the development of super-resolved fluorescence microscopy. Their groundbreaking work brought optical microscopy into the nanoworld. "Today, nanoscopy is used world-wide, and new knowledge of greatest benefit to mankind is produced on a daily basis."[②] Since 1873, when Ernst Abbe first proposed the rule of diffraction-limited imaging, researchers believed that the ability to resolve two nearby points was fundamentally limited by the wavelength of light. This physical insight became one of the most prominent paradigms in the natural sciences, with paramount importance in biology (Hell, 2003).

More than a century later, Stefan W. Hell, now director of the Max Planck Institute of Biophysical Chemistry, was the first to demonstrate, theoretically and experimentally, that one can use a light microscope to resolve objects on the nanometer scale, below the diffraction limit (Chi, 2009). A scientific history article from *Nature Methods* in 2008 reviewed the development history and key persons in the field of super-resolution microscopy, which provided a good overview of the scientific history of this field (Chi, 2009).

Figure 1 illustrates Stefan W. Hell's education, working, and publication information from his personal profile website[③]. When pursuing his postgraduate study, Hell first realized that it would be possible to improve resolution by using not just a single lens to focus light onto a point, but two large-aperture lenses jointly. After he completed his PhD thesis in 1990, he devised the 4Pi microscope based on this idea. However, many researchers, including prominent physicists, thought that Hell would not get very far in improving resolution.

In 1992, he showed for the first time that the 4Pi microscope could improve the resolution of a conventional microscope three to seven times. Yet, he was not able to overcome the diffraction limit. During his next postdoctoral stint, he thought of the idea that, with the right lasers, he could fluorescently activate a spot, and then shrink that spot by depleting the emission in a doughnut-shaped area surrounding it. He would later call this imaging method "stimulated emission depletion" (STED).

In 1994, Hell published the theory of STED in *Optics Letters* (Hell & Wichmann, 1994). But Abbe's rule was still looming large. Many physicists were resistant to Hell's ideas and focused on other imaging methods. Despite this, in 1997, Hell was

② http://www.nobelprize.org/nobel_prizes/chemistry/laureates/2014/press.html?utm_source=twitter&utm_medium=social&utm_campaign=twitter_tweet
③ http://www3.mpibpc.mpg.de/groups/hell/

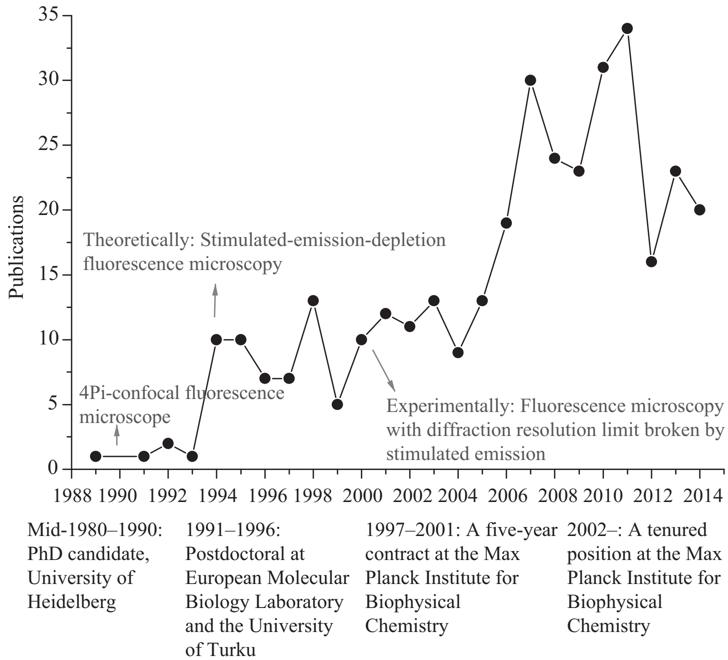

Figure 1. Stefan W. Hell's education, working, and publication profile.

offered a five-year contract at the Max Planck Institute for Biophysical Chemistry to demonstrate that STED works. In 1999, he sent the resulting manuscript to *Nature* and *Science*, but was rejected. In 2000, *PNAS* published the data, in which STED was used to produce the first truly nanoscale fluorescence images (Klar et al., 2000), and Hell obtained a tenured position at the Institute in 2002, where he continued to develop and apply new imaging methods.

Since this pioneering work, a number of super-resolution techniques have been developed. Researchers led by Mats Gustafsson proposed Structured Illumination Microscopy (SIM) in 2000 (Gustafsson, 2000). In 2006, opening a new chapter in the development of the field, three groups simultaneously reported that they had increased resolution using yet another approach. Eric Betzi's group published their Photoactivated Localization Microscopy (PALM) method (Betzig et al., 2006). Samuel T. Hess's group reported on their Fluorescence Photoactivation Localization Microscopy, FPALM (Hess, Girirajan, & Mason, 2006). Xiaowei Zhuang's group developed Stochastic Optical Reconstruction Microscopy, STORM (Rust, Bates, & Zhuang, 2006).

Hell's scientific history and subsequent major developments of the field demonstrated that physics undoubtedly has greatly contributed to the emergence of molecular and cell biology in the past century. Paradoxically, the development of nanoscale imaging with focused light in molecular and cell biology might now topple a longstanding paradigm of physics. Based on the above statements, we reasoned that the *Optics Letters* article in 1994, Hell (1994) for short, can be considered an SP while the *PNAS* article in 2000, Hell (2000) for short, is its PR. This will be investigated in the next section.

3.2 The Bibliometric Framework

We collected the citation data of Hell (1994) from the Web of Science Core Collection on 31 December, 2014, resulting in 1,210 citations. As illustrated in Figure 2, Hell (1994) was a "genius work" according to the citation curve, and was also a typical SB paper. "Genius work," proposed by Avramescu (1979), refers to scientific articles whose citations grow exponentially over an extended period.

During nearly a decade after its publication, it received few citations. These began to increase in 2003, followed by substantial growth from 2005 to 2007. Citations per year grew exponentially over a 20-year period. Hell (1994) was cited 30 times during the 9 years after its publication; 12 (40%) were self-citations, which indicates that Hell firmly believed in the value of his theory and continued working on it and its implications.

Among other early citations, the 2014 Nobel Prize winners Eric Betzig, William E. Moerner, and other famous authors such as Xiaowei Zhuang and Samuel T. Hess are absent. Only Mats Gustafsson cited Hell (1994), in a review article published in *Current Opinion in Structural Biology* in 1999. On average, Hell (1994) received only two citations per year, excluding self-citations. Based on our criteria, we will verify whether the bibliometric framework can discern Hell (2000) as a PR document and investigate whether other PR articles also exist.

3.3 Co-citation Analysis

Hell (1994) was cited 1,210 times over the 1994–2014 period. We scanned the reference list of the 1,210 citing articles, and the most co-cited documents with Hell (1994) were identified. Documents with more than 10% co-citations (that is, at least 121 co-citations) were regarded as candidate PRs for the SB (Table 1). We investigated whether the candidate PR documents are the key publications in winning the Nobel Prize, whether the candidate PR cited the SB, and whether the candidate PR's citations and co-citations with the SB fell between 1994 and 2014. We also examined whether the candidate PR documents meet the four criteria (C1–C4) proposed above.

As summarized in Table 1, more than 80% (17 in 21) of the most co-cited references with Hell (1994) are authored by the prominent scholars who significantly

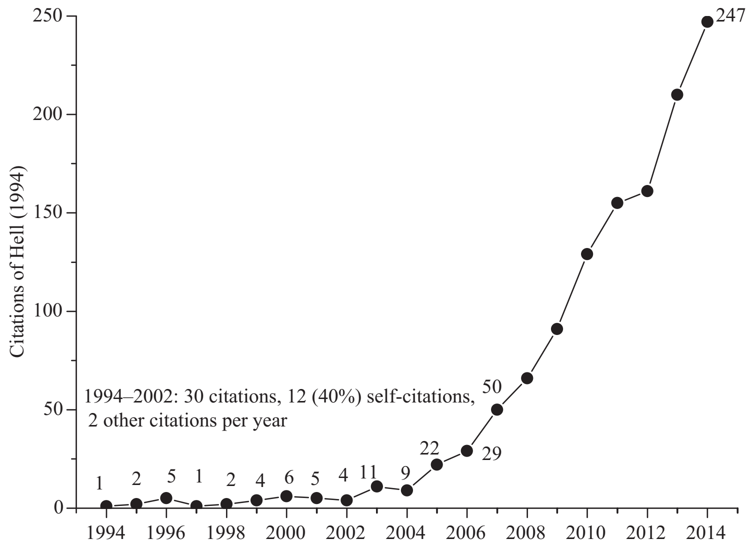

Figure 2. Citation curve of Hell (1994).

contributed to the research field, such as Hell himself (9/17), Zhuang (3/17), Gustafsson (3/17), Betzig (1/17), and Hess (1/17), as stated in the "scientific history" section. We then identified four selected PR articles which were published around the time of the SB's awakening, and during which the annual number of citations of the PR is more than the SB's—i.e. they must have prompted the authors of subsequent related works to refer to the SB.

Figure 3 shows the citation curves of the SB and the selected four PRs, as well as the co-citation curve of each SB-PR pair. We can clearly see the "pulling effect" of the four selected PRs on the SB's citation increase, demonstrating a dynamic and continuous triggering process. Hell (1994)'s citations were first induced by Hell (2000), and then by Hell (2003), and then by Rust (2006) and Betzig (2006), which are short for Rust, Bates, and Zhuang (2006) and Betzig et al. (2006), respectively. This last is one of key publications of the award. In the graphs, it seems that the four papers have a boosting effect on the SB, bringing it to the attention of the scientific community.

Hell (1994) and Hell (2000) represented the landmark theoretical and experimental papers on STED, respectively. According to the citation curves in Figure 3, the citations of Hell (1994) did not increase rapidly immediately after STED was proved in 2000. It was not until 2003 that the citations of Hell (1994) began to show a clear increasing trend.

Since 2006, annual citations of the landmark experimental paper started to lag behind the landmark theoretical paper. Such a trend can also be observed in Hell

Table 1. The candidate PR documents.

	KP	Citing the SB	Citations	Co-citations	Cited references	C1	C2	C3	C4
1	Y *		1,210	1,210	**Hell** (1994), *Opt Lett*, V19, P780				
2	Y	N	1,642	594	Rust (2006), *Nat Methods*, V3, P793 **(Zhuang)**	√	√	√	√
3	Y *	N	2,006	590	**Betzig** (2006), *Science*, V313, P1642	√	√	√	√
4	Y	N	1,013	361	**Hess** (2006), *Biophys J*, V91, P4258	√	√	√	
5		Y	1,109	314	**Hell** (2007), *Science*, V316, P1153	√	√	√	
6	Y	Y	678	297	**Gustafsson** (2005), *P Natl Acad Sci USA*, V102, P13081	√	√	√	
7	Y *	Y	571	265	Klar (2000), *P Natl Acad Sci USA*, V97, P8206 **(Hell)**	√	√	√	√
8	Y	Y	597	258	**Gustafsson** (2000), *J Microsc-Oxford*, V198, P82	√	√	√	
9	Y	/	742	204	**Abbe** (1873), *Arch Mikrosk Anat*, V9, P413		√	√	
10		N	661	187	Huang (2008), *Science*, V319, P810 **(Zhuang)**		√	√	
11		N	4,985	179	Denk (1990), *Science*, V248, P73		√	√	
12	Y	Y	470	166	**Hell** (2003), *Nat Biotechnol*, V21, P1347	√	√	√	√
13		Y	314	157	Westphal (2008), *Science*, V320, P246 **(Hell)**		√	√	
14		Y	395	155	Heilemann (2008), *Angew Chem Int Edit*, V47, P6172		√	√	
15		N	248	151	Heintzmann (2002), *J Opt Soc Ama*, V19, P1599	√	√	√	
16		N	879	149	Thompson (2002), *Biophys J*, V82, P2775	√	√	√	
17		Y	281	145	Hofmann (2005), *P Natl Acad Sci USA*, V102, P17565 **(Hell)**	√	√	√	
18	Y *	Y	176	139	**Hell** (1995), *Appl Phys B-Lasers O*, V60, P495		√	√	
19		Y	405	138	Willig (2006), *Nature*, V440, P935 **(Hell)**	√	√	√	
20		Y	382	134	**Hell** (2009), *Nat Methods*, V6, P24		√	√	
21		N	443	130	Bates (2007), *Sciecne*, V317, P1749 **(Zhuang)**	√	√	√	
22		Y	236	124	Donnert (2006), *P Natl Acad Sci USA*, V103, P11440 **(Hell)**	√	√	√	

Note. KP, * denotes key publications of the award, Y denotes that the article is in the reference list of *Scientific Background on the Nobel Prize in Chemistry 2014*, provided by the Nobel Committee for Chemistry[④]; Citing the SB, Y denotes that the documents cite the SB, N that it does not cite the SB but does cite Hell's other relevant papers; Text in bold indicates that the person, either as the first author or the corresponding author in the cited references, is the representative figure in the "scientific history" section.

[④] http://www.nobelprize.org/nobel_prizes/chemistry/laureates/2014/advanced-chemistryprize2014.pdf

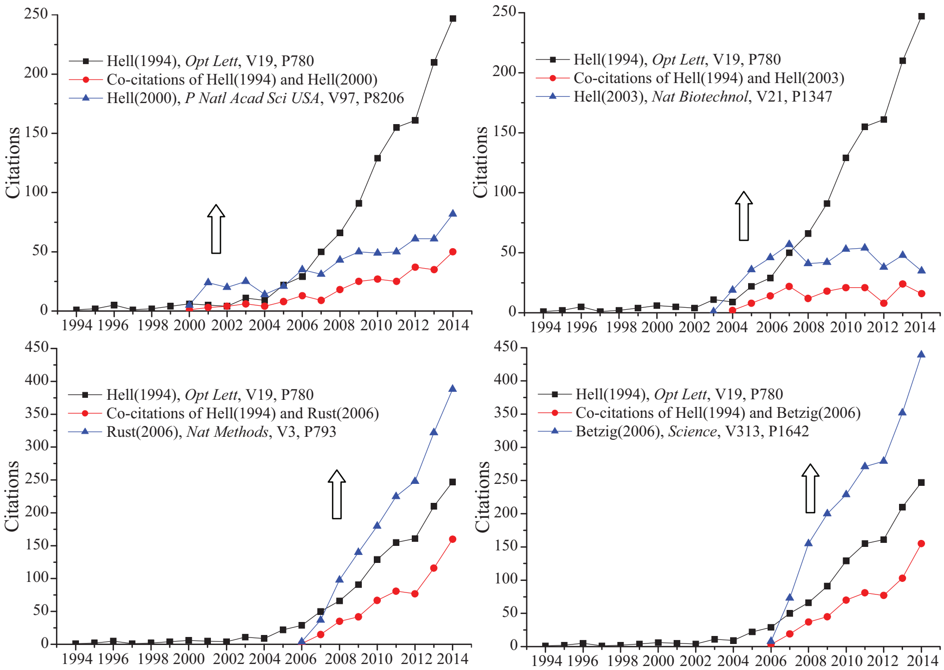

Figure 3. The citation curves of the SB and the four selected PR articles.

(1994) and Hell (2003); the citation curves of the SB-PR combinations are almost entirely consistent with the PR and not those of the SB. This indicates that new developments have likely emerged concerning high-resolution fluorescence microscopy, which extended Hell's STED concept and practice. After all, as a pioneering paper in this field, the theoretical contribution of Hell (1994) was the first to break the traditional paradigm, so any developments in this field would inevitably cite the groundbreaking work. We therefore continue to investigate how other key actors, Rust (2006) and Betzig (2006), contributed to the sharp increase of Hell (1994)'s citations in terms of content analysis.

3.4 The Content Analysis

The first-ranked candidate PR article is just Hell (2000), which indicates that our identification of the PR document in terms of the bibliometric framework is in line with historical facts. The successful application of STED invoked recognition of the STED theory. From Hell's comments to Hell (1994) in the 12 self-citing documents, it can be seen that Hell insisted on the value of his work, despite resistance. He believed that Hell (1994) was the first idea and Hell (2000) the first successful evidence in breaking Abbe's barrier.

The title of Hell (2003) is "*Towards fluorescence nanoscopy*," which is a perspective article in *Nature Biotechnology*. It cited Hell (1994) twice, and highly praised the work of Hell (1994). In Hell (2003), Hell (1994) was described as the first report on a viable concept in challenging Abbe's diffraction limit, and Hell (1994)'s principle established a whole family of methods for achieving nanoscale resolution in all directions. We can conclude that Hell (2003) provides good clues for subsequent scholars to learn about Hell's ideas.

Different from Hell's STED methods, the single-fluorophore-based methods by both Betzig (2006) and Rust (2006) also served as driving forces for Hell (1994) citations. As is shown in the citation network of Rust (2006) and Betzig (2006), and their citation relations to the SB (Figure 4), neither Betzig (2006) nor Rust (2006) directly cited Hell (1994), nor did they cite each other.

After examining their cited references, we found that Rust (2006) cited Hell (2003) and a document published by Hell in 2005 (*PNAS*, V102, P17565, Michael Hofmann as the first author), Hell (2005) for short. Betzig (2006) also cited Hell (2005) and an article published by Hell in *Nature* in 2006, with Katrin I. Willig as first author. Hell (2005) is just an intermediate paper.

We read the citation content of these documents and found Hell (2005) also cited and described Hell (1994) as "an important research advance." Rust (2006) considered Hell (2003) "a research finding that broke Abbe's diffraction limit." Betzig (2006) and Rust (2006) respectively described Hell (2005) as "significant progress" and "a research under way." All articles mentioned above are in the list of the candidate PR documents with the most co-citations with the SB in Table 1. Betzig (2006) and Rust (2006) are the second-generation citing articles for Hell (1994).

Integrating scientific history with a bibliometric framework, we identified four documents that played important roles in awakening Hell (1994), two of which were authored by Hell himself: Hell (2000) and Hell (2003). The former was a successful practical application of the theory proposed by the SB, while the latter perspective article that spoke highly of the research findings of the SB. These two documents were the PRs.

Betzig (2006) and Rust (2006) were successful successors of Hell (1994)'s novel idea; they brought high-resolution microscopy into a "prosperous time." High-resolution microscopy was celebrated as one of the ten breakthroughs of 2006 by *Science*, and was also selected as the "best method" by *Nature Methods* in 2008. Just before the announcement of the 2014 Nobel Prize, the innovative technology was again in the list of the top ten technologies of the preceding 10 years in *Nature Methods*. The development of high-resolution microscopy indeed enabled a brand new insight for scientists in the field of molecular and cell research.

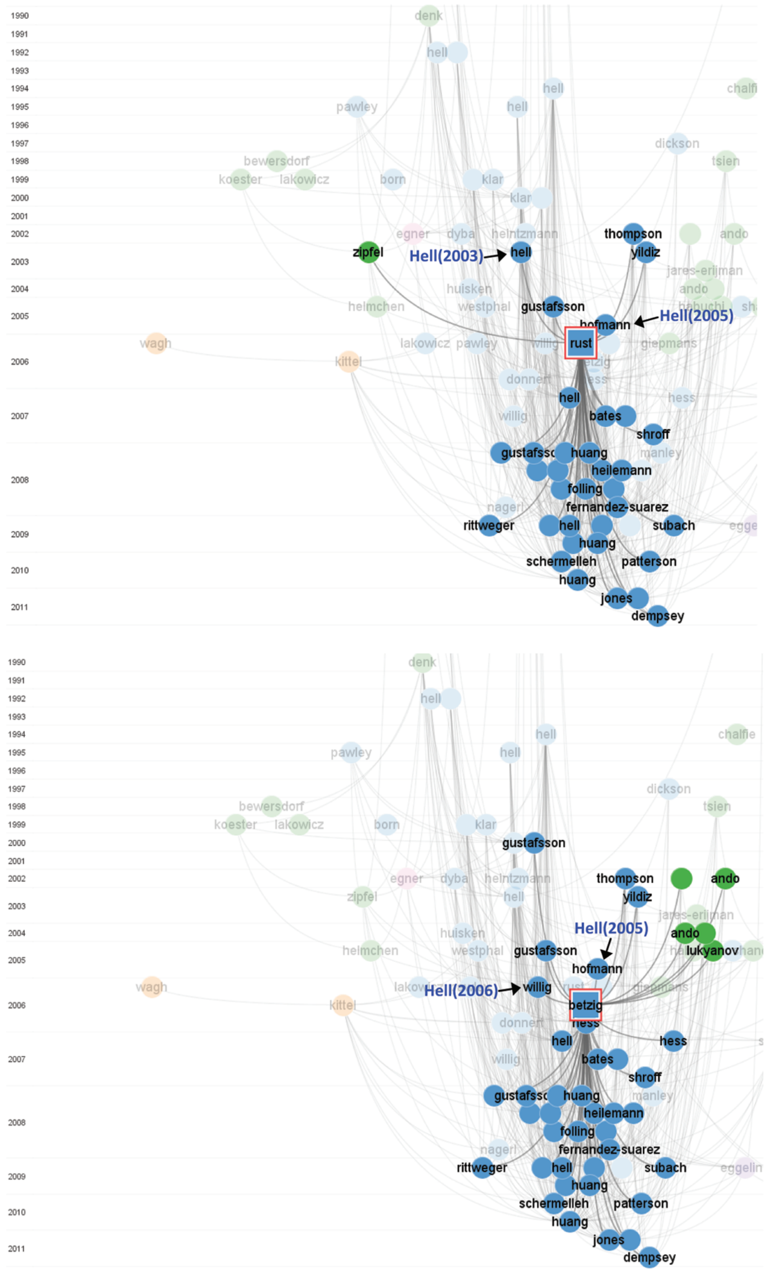

Figure 4. The citation networks of Rust (2006) and Betzig (2006).

All of these factors induced the citation leap of Hell (1994). In ancient China, the "retinues" are always referred to as the attendants of the "nobles" or "princes." The above analysis has showed that Hell himself is a PR, and Betzig and Zhuang followed and developed the theory created by Hell; so Betzig (2006) and Rust (2006) may be regarded as "the retinues of the prince".

4 Discussions and Conclusions

In our previous work (Du & Wu, 2015), we concluded that by examining the reference list of articles citing the SB, one can discern the PR articles characterized by the following features: (1) they were published not long after the SB's awakening; (2) they are highly co-cited with the SB; 3) they have almost the same co-citation speed and "co-delayed recognition index" with the SB. But it seems a tough task when we first tentatively calculate the value of every document's co-citation speed and "co-delayed recognition index" with the SB, and then compare them with those of the SB. Since the scientific community regards the discovery in Hell (1994) as transformative innovation, in the present study, we try to develop and validate a simplified framework to identify the PRs.

In this paper, we not only found that Hell (2000) is the first PR, but also detected another PR, — i.e. Hell (2003) — and two "retinues" of the PR, Betzig (2006) and Rust (2006). It seems that these four documents (two PRs and two retinues) introduced Hell (1994) to subsequent scholars and thus made her an SB. By examining the reference list of articles citing SBs, one can discern PR articles by means of our bibliometric framework.

Our study also confirmed and improved the characteristics of PRs summarized by Braun, Glänzel, and Schubert (2010). First, they are published around the SB's awakening. Second, they are highly cited papers and highly co-cited with the SB. Third, they are supposed to demonstrate an obvious pulling effect on the SB, especially in case of transformative innovations. Using the concept of Kuhn's "paradigm," there are two kinds of innovative research — cumulative processes and revolutionary breakthroughs. The bibliometric framework is more suitable for the latter. Publications belonging to so-called transformative research, when less-cited, may be given special attention, because they may suddenly attract a lot of attention after a period of time, as reflected in our case study.

Finally, an SB may need a PR plus other agents to wake her up, and documents with potential awakening functionality tend to be published in multidisciplinary and prestigious journals with higher impact and wider scope than the journals publishing SBs. For example, *PNAS*, *Nature Biotechnology*, *Nature Methods*, and *Science* contrast with *Optical Letters* in our case study. The rapid application of super-resolution microscopy developed by physics scientists are already applied on a large scale in major fields of biology and life sciences, such as cell biology, microbiology, and neurobiology (Huang, Babcock, & Zhuang, 2010). Now, scientists are active in introducing new developments of other disciplines into their own research. Interdisciplinary research promotes the evolution of science (Fang, 2014). In many cases, the SB phenomenon occurs when research finds application in a field outside of its own, such as statistical methods that become useful in biology.

A sleeping beauty may need one or more "princes" and even "retinues" to be awakened. The PRs may be either conceptually related or direct-citation-related to the SB. In this study, the PRs include two documents of Hell himself, who believed and insisted on his theory, and finally succeeded. Although the other two PRs did not cite the SB in the first generation, they cited other documents of Hell, and these citations induced the citation leap of the SB. Hell did not co-author with Betzig's group or Zhuang's group; it is through a knowledge relationship (citation) that they contributed to the citation leap of the SB.

The study of the SB and her PRs has been considered "a rather useful and instructive model in studying the mechanisms of scientific information flow through citations" (Braun, Glänzel, & Schubert, 2010), and is likely to contribute to the understanding of citation dynamics in general. The key scientific issues of the study towards SBs is to figure out the mechanisms for awakening, in order to promote potentially valuable but not readily accepted innovative research (Fang, 2014; Wang et al., 2012). Trapido (2015) discussed why novelty is sometimes an advantage and sometimes a liability, and what is required for highly novel knowledge to earn evaluating audiences' recognition, rather than neglect or skepticism. If the scientific community could learn more lessons from previous resistance to discoveries, the dilemma of science opposing innovation will be at least partially solved (Fang, 2014). The above conclusions are drawn from a detailed analysis of a typical SB and her awakening process. It requires further empirical study to investigate whether the conclusions can be expanded to other SBs or fields besides chemistry and physics.

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Author Contributions

J. Du (windowsdujian@163.com) planned the outline, performed data analysis, wrote the first draft, and joined discussion of the findings. Y. S. Wu (wuyishan@istic.ac.cn, corresponding author) improved the research design, polished the manuscript, and contributed to the revised version of the manuscript.

References

Avramescu, A. (1979). Actuality and obsolescence of scientific literature. Journal of the American Society for Information Science, 30(5), 296–303.

Barber, B. (1961). Resistance by scientists to scientific discovery. Science, 134(3479), 596–602.

Betzig, E., Patterson, G. H., Sougrat, R., Lindwasser, O. W., Olenych, S., Bonifacino, J. S., Davidson, M.W., Lippincott-Schwartz, J., & Hess, H. F. (2006). Imaging intracellular fluorescent proteins at nanometer resolution. Science, 313(5793), 1642–1645.

Braun, T., Glänzel, W., & Schubert, A. (2010). On sleeping beauties, princes and other tales of citation distributions. Research Evaluation, 19(3), 195–202.

Burrell, Q. L. (2005). Are "sleeping beauties" to be expected? Scientometrics, 65(3), 381–389.

Campanario, J. M. (2009). Rejecting and resisting Nobel class discoveries: Accounts by Nobel laureates. Scientometrics, 81(2), 549–565.

Chi, K. R. (2009). Super-resolution microscopy: Breaking the limits. Nature Methods, 6(1), 15–18.

Cole, S. (1970). Professional standing and the reception of scientific discoveries. American Journal of Sociology, 76(2), 286–306.

Costas, R., van Leeuwen, T. N., & van Raan, A. F. J. (2010). Is scientific literature subject to a "sell-by-date"? A general methodology to analyze the "durability" of scientific documents. Journal of the American Society for Information Science and Technology, 61(2), 329–339.

Costas, R., van Leeuwen, T. N., & van Raan, A. F. J. (2011). The "Mendel syndrome" in science: Durability of scientific literature and its effects on bibliometric analysis of individual scientists. Scientometrics, 89(1), 177–205.

Costas, R., van Leeuwen, T. N., & van Raan, A. F. J. (2013). Effects of the durability of scientific literature at the group level: Case study of chemistry research groups in the Netherlands. Research Policy, 42(4), 886–894.

Du, J., & Wu, Y. S. (2015). Defining and identifying the sleeping beauty and her princes in science (in Chinese). Library and Information Service, 59(19), 84–92.

Du, J. & Wu, Y. S. (2015). Identifying "sleeping beauties" and the princes who woke up sleeping beauties in terms of citation speed measures: A case study of the key publications by Stefan W. Hell (in Chinese). Journal of the China Society for Scientific and Technical Information, 34(5), 508–521.

Förster, J., Friedman, R. S., & Liberman, N. (2004). Temporal construal effects on abstract and concrete thinking: Consequences for insight and creative cognition. Journal of Personality and Social Psychology, 87(2), 177–189.

Fang, H. (2015). An explanation of resisted discoveries based on construal-level theory. Science and Engineering Ethics, 21(1), 41–50.

Florence, A. T. (2015). Cited but not read and read but not cited. International Journal of Pharmaceutics, 492(1–2), 264–265.

Garfield, E. (1970). Would Mendel's work have been ignored if the Science Citation Index was available 100 years ago? Current Contents, 2, 69–70.

Garfield, E. (1980). Premature discovery or delayed recognition-why? Current Contents, 21, 488–493.

Garfield, E. (1989). Delayed recognition in scientific discovery: Citation frequency analysis aids the search for case histories. Current Contents, 23, 3–9.

Garfield, E. (1990). More delayed recognition. Part 2. From inhibin to scanning electron microscopy. Current Contents, 9, 3–9.

Glänzel, W., & Garfield, E. (2004). The myth of delayed recognition. Scientist, 18(11), 8.

Glänzel, W., Schlemmer, B., & Thijs, B. (2003). Better late than never? On the chance to become highly cited only beyond the standard bibliometric time horizon. Scientometrics, 58(3), 571–586.

Gorry, P., & Ragouet, P. (2015). Charles Dotter and the birth of interventional radiology: A "sleeping-beauty" with a restless sleep. In Proceedings of ISSI 2015 Istanbul, 15th International Society of Scientometrics and Informetrics Conference (pp. 266–271). Istanbul, Turkey: Boğaziçi University Printhouse.

Gustafsson, M. G. L. (2000). Surpassing the lateral resolution limit by a factor of two using structured illumination microscopy. Journal of Microscopy, 198(2), 82–87.

Hell, S. W. (2003). Towards fluorescence nanoscopy. Nature Biotechnology, 21(11), 1347–1355.

Hell, S. W., & Wichmann, J. (1994). Breaking the diffraction resolution limit by stimulated-emission: Stimulated-emission-depletion fluorescence microscopy. Optics Letters, 19(11), 780–782.

Hess, S. T., Girirajan, T. P. K., & Mason, M. D. (2006). Ultra-high resolution imaging by fluorescence photoactivation localization microscopy. Biophysical Journal, 91(11), 4258–4272.

Huang, B., Babcock, H., & Zhuang, X. (2010). Breaking the diffraction barrier: Super-resolution imaging of cells. Cell, 143(7), 1047–1058.

Ke, Q., Ferrara, E., Radicchi, F., & Flammini, A. (2015). Defining and identifying sleeping beauties in science. Proceedings of the National Academy of Sciences of the United States of America, 112(24), 7426–7431.

Klar, T. A., Jakobs, S., Dyba, M., Egner, A., & Hell, S. W. (2000). Fluorescence microscopy with diffraction resolution barrier broken by stimulated emission. Proceedings of the National Academy of Sciences of the United States of America, 97(15), 8206–8210.

Knottnerus, J. A., & Knottnerus, B. J. (2009). Let's make the studies within systematic reviews count. The Lancet, 373(9675), 1605.

Koshland Jr, D. E. (2007). The Cha-Cha-Cha theory of scientific discovery. Science, 317(5839), 761–762.

Kozak, M. (2013). Current science has its "sleeping beauties". Current Science, 104(9), 1129.

Kuhn, T. S. (1962). The structure of scientific revolutions. Chicago: University of Chicago Press.

Lachance, C., & Larivière, V. (2014). On the citation lifecycle of papers with delayed recognition. Journal of Informetrics, 8(4), 863–872.

Lange, L. L. (2005). Sleeping beauties in psychology: Comparisons of "hits" and "missed signals" in psychological journals. History of Psychology, 8(2), 194–217.

Li, J. (2014). Citation curves of "all-elements-sleeping-beauties": "Flash in the pan" first and then "delayed recognition". Scientometrics, 100(2), 595–601.

Li, J, & Shi, D. B. (2015). Sleeping beauties in genius work: When were they awakened? Journal of the Association for Information Science and Technology, 67(2), 432–440.

Li, J., Shi, D. B., Zhao, S. X., & Ye, F. Y. (2014). A study of the "heartbeat spectra" for "sleeping beauties". Journal of Informetrics, 8(3), 493–502.

Li, J., & Ye, F. Y. (2012). The phenomenon of all-elements-sleeping-beauties in scientific literature. Scientometrics, 92(3), 795–799.

Li, S., Yu, G., Zhang, X., & Zhang, W. F. (2014). Identifying princes of sleeping beauty - Knowledge mapping in discovering princes. In Proceedings of the 21st International Conference on Management Science and Engineering (pp. 912–918). Helsinki, Finland, IEEE.

Liberman, N., Trope, Y., McCrea, S. M., & Sherman, S. J. (2007). The effect of level of construal on the temporal distance of activity enactment. Journal of Experimental Social Psychology, 43(1), 143–149.

Marks, M. S., Marsh, M. C., Schroer, T. A., & Stevens, T. H. (2013). An alarming trend within the biological/biomedical research literature towards the citation of review articles rather than the primary research papers. Traffic, 14(1), 1.

Marx, W. (2014). The Shockley-Queisser paper—A notable example of a scientific sleeping beauty. Annalen der Physik, 526(5–6), A41–A45.

Mazloumian, A., Eom, Y. H., Helbing, D., Lozano, S., & Fortunato, S. (2011). How citation boosts promote scientific paradigm shifts and Nobel Prizes. PLOS One, 6(5).

Ohba, N., & Nakao, K. (2012). Sleeping beauties in ophthalmology. Scientometrics, 93(2), 253–264.

Redner, S. (2005). Citation characteristics from 110 years of Physical Review. Physics Today, 58(6), 49–54.

Rousseau, R. (2007). Cha-cha-cha in informetrics. ISSI Newsletter, 3(3), 43–45.

Rust, M. J., Bates, M., & Zhuang, X. W. (2006). Sub-diffraction-limit imaging by stochastic optical reconstruction microscopy (STORM). Nature Methods, 3(10), 793–795.

Stent, G. S. (1972). Prematurity and uniqueness in scientific discovery. Scientific American, 227(6), 84–93.

Sun, J. J., Min, C., & Li, J. (2015). A vector for measuring obsolescence of scientific articles. In Proceedings of ISSI 2015 Istanbul, the 15th International Society of Scientometrics and Informetrics Conference (pp. 317–327). Istanbul, Turkey: Boğaziçi University Printhouse.

Trapido, D. (2015). How novelty in knowledge earns recognition: The role of consistent identities. Research Policy, 44(8), 1488–1500.

Trope, Y., & Liberman, N. (2010). Construal-level theory of psychological distance. Psychological Review, 117(2), 440–463.

van Calster, B. (2012). It takes time: A remarkable example of delayed recognition. Journal of the American Society for Information Science and Technology, 63(11), 2341–2344.

van Raan, A. F. J. (2004). Sleeping beauties in science. Scientometrics, 59(3), 467–472.

van Raan, A. F. J. (2015). Dormitory of physical and engineering sciences: Sleeping beauties may be sleeping innovations. PLOS One, 10(10), e0139786.

Wang, J., Ma, F., Chen, M., & Rao, Y. (2012). Why and how can sleeping beauties be awakened? Electronic Library, 30(1), 5–18.