

Review Article

Jiao Wang*, Yaoyao Chen, Guangyu Liu, Weiming Cheng, and Tong Yin

How has Lunar science developed? A bibliometric analysis and systematic review

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Abstract: Lunar exploration is a significant process to unravel the evolutionary history of the Earth-Moon system and the pivotal foundation for the exploration of the solar system. A total of 49,161 articles recorded in a comprehensive online literature database between 1959 and 2018 were reviewed to address the development of lunar science in six aspects: publication output volume, keywords, journals, authorship, collaboration, and national output efficiency. The development of lunar science experienced rise and fall corresponding to a log-linearized model that could be clearly divided into three stages: space race (1959-1977), silent stage (1978-1996) and renaissance (1997-2018). Keywords extracted from publications as reliable predictors of multidiscipline showed that the well-developed disciplines of lunar science were astronomy, space engineering, earth and planetary science, while other disciplines played important roles in different stages. Researchers had become cooperative rather than independent in publishing in the past sixty years. Countries with higher average annual GDP contributed more to the development of lunar science. The findings of this work help scholars comprehend the development of lunar science for the past, present and future.

Keywords: Lunar science, bibliometrics, publication output, multidiscipline, authorship, scientific collaboration, gross domestic product

1 Introduction

Broadus (1987) defined bibliometrics as the quantitative study of physically published units, or of bibliographic units, or of alternatives of either. It has been employed in a wealth of academic disciplines to help researchers, as well as general public, get the newest scientific achievements, tell magnificent scientific stories in appropriate academic journals, communicate with leading researchers in interested fields, join in influential scientific institutions and contribute to the development of disciplines (Borgman and Furner 2002). Although the explosive growth of scientific

publications recording industrialization of science raises the cost of bibliometric analysis, computerized methods like data mining, data visualization, semantic analysis, and parallel computing solve this problem with their processing power (Mingers and Leydesdorff 2015). Taking into account the advantage and adjustability, the bibliometric analysis of scientific publications has broad application in emerging disciplines to understand their nature and predict their future (Barbosa *et al.* 2017).

The bibliometric analysis of scientific publications has been carried in a bunch of academic disciplines, including the biomedicine and related sciences (Bordons *et al.* 2013; Winnink and Tijssen 2014), the physical geography (Peng *et al.* 2015; Piégay *et al.* 2015; Maisonnobe *et al.* 2017), the human geography (Wang and Liu 2014), the information technology (Tian *et al.* 2008; Bornmann 2015; Liu *et al.* 2016), the knowledge management (Gu 2004; Serenko *et al.* 2010; Sooryamoorthy 2018), and the economics (Bochove 2013; Inglesi-Lotz *et al.* 2014; Chang and Ho 2010). While other disciplines like lunar science are nearly neglected. There are a few typical works have been done on the astronomical field to which lunar science is related. White (1992) surveyed two major astronomical journals for the 30-year period 1960-1989 looking for papers with either principal or co-authors from developing countries: formerly com-

Corresponding Author: Jiao Wang: School of Information Engineering, China University of Geosciences, Beijing 100083, China; State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; Email: jiaowang@cugb.edu.cn

Yaoyao Chen, Guangyu Liu: School of Information Engineering, China University of Geosciences, Beijing 100083, China

Weiming Cheng: State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

Tong Yin: Research Institute of Surveying and Mapping Standardization, Ministry of Natural Resources, Xi'an 710054, China

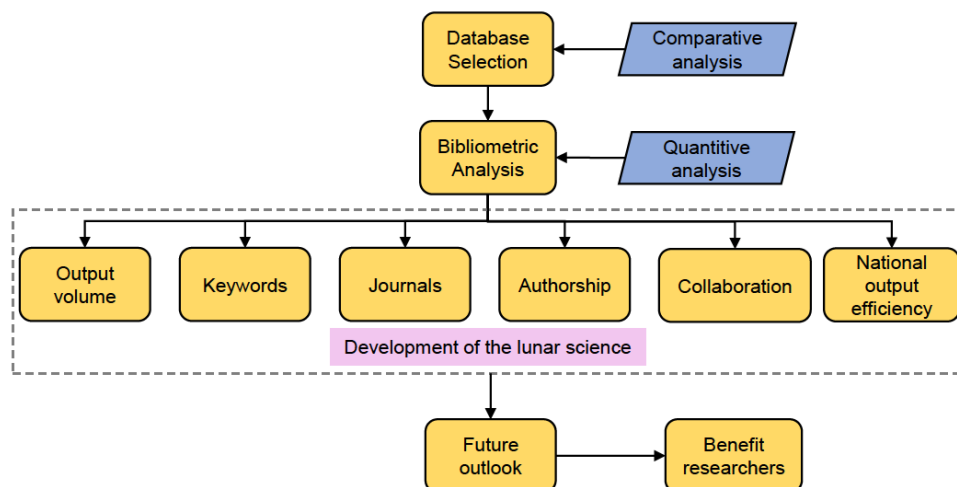


Figure 1. The workflow of bibliometric analysis of lunar science.

munist Eastern European countries, and the former Soviet Union. Kurtz *et al.* (2005) introduced the concept of utility time to measure the impact of the Astrophysics Data System (ADS) and the electronic astronomical library on astronomical research. Hearnshaw (2006) used published astronomical outputs in different countries as a measure of astronomical activity. He found that a roughly three-fold increase in the number of published papers per year from 1976-2005, both in developed and most developing countries. Smith (2016) documented the change of publication habits of astronomers and found the astronomers have become increasingly collaborative according to data from four typical journals about the astronomy. However, it's not adequate to complete a comprehensive study and provide a clear indication of the developing trends or future orientation of a research field by using limited journals and papers correlated to a special phenomenon.

The study of the Moon has attracted great attention from human beings in several projects of planetary exploration owing to the Moon's relative proximity to the Earth. Generally, scientists study the Moon in eight areas including the exploration of the Moon, the evolution of the Moon, the surface analysis of the Moon, the environment of the Moon, the astrophysics of the Moon, the astrochemistry of the Moon, the remote sensing of the Moon and the comparative planetology, which need researchers from different scientific fields to cooperate. The accelerating pace of lunar exploration in the last two decades with the fast development of orbit and remote sensing techniques has resulted in abundant data, which have revolutionized our knowledge of the Moon (Baker 2015). The interdisciplinary nature of lunar science attracts researchers from various scientific or social fields to study the Moon from different aspects in-

cluding astrophysical, engineering, material, geo-scientific and philosophical (Crawford *et al.* 2014). The evolutionary history and multidiscipline of lunar science, however, are seldom analyzed in a quantitative and systematic way on the basis of scientific publications through increasingly accessible data sources. In this study, we have evaluated lunar science from the perspective of bibliometrics to discover future research points, considering the fact that promoting planetary exploration benefits our human beings.

The goal of this paper is to map the development of lunar science by doing a bibliometric analysis of published lunar outputs from 1959 to 2018. Before going into more details in the bibliometric analysis, a proper database is filtered by going through existed online databases considering the specialty and multidiscipline of lunar science. Then, the publication output volume, the keywords, the journals, and the authorship changed over time are examined to uncover the evolutionary history of lunar science. In addition, the prominent institutions and collaborative communities are identified by analyzing the geographic origin of the authors' affiliation. The present study also sheds new light on the relationship between lunar research and gross domestic product (GDP) of a nation to measure the national output efficiency (Figure 1).

2 Data and method

2.1 Database selection

To guarantee the comprehensiveness of data collection, five typical online databases were examined. By December 2018, Scopus is one of the largest bibliographic and cita-

Table 1. The basic information about selected online literature databases.

Database	No. of journals	Time range	No. of fields	No. of disciplines	No. of subject categories	No. of lunar science journals	Research Concern %
ADS	4,236	1993-ongoing	2	-	-	68	1.6
Scopus	35,077	2004-ongoing	5	27	307	71	0.2
WoS	24,108	1900-ongoing	5	-	234	68	0.3
SL	3,409	1996-ongoing	-	47	926	23	0.7
WOL	2,451	2010-ongoing	-	17	125	10	0.4

tion databases including 35,077 active journals that belong to 27 main subject areas and 307 subject categories with the depth of coverage dating back to 1966. It's a comprehensive database that allows researchers to navigate in its multidisciplinary disciplines easily. Web of Science (WoS) is now maintained by Clarivate Analytics including seven citation indexes covering 24,108 journals. Science Citation Index Expanded, as one of its well-known citation indexes, covers more than 8,500 notable journals encompassing 150 disciplines and the coverage is from the year 1900 to the present day. SpringerLink (SL) is launched in 1996 by academic publisher Springer-Verlag containing 3,409 journals belong to 47 sub-disciplines. Wiley Online Library (WOL) is a subscription-based library of John Wiley and Sons launched in 2010, which provides online access to a broad range of contents from over 1,600 journals covering life, health, and physical sciences as well as social science and the humanities (Archambault *et al.* 2009). The advantage of these four databases is the elaborated classification of scientific disciplines. In contrast, the searched results from these comprehensive databases usually mixed with unrelated information even filtered with conditioning expressions. Except for the above comprehensive databases, National Aeronautics and Space Administration-Astrophysics Data System (NASA-ADS) is a dominant database by which astronomers search, access and read their technical literature. The ADS maintains three bibliographic databases containing more than 13 million records covering publications in Astronomy and Astrophysics, Physics, and the arXiv e-prints (Kurtz *et al.* 2000) since 1513. It should be pointed out that ADS has more conference proceedings and abstracts, as well as journals which had not been issued for years about lunar science comparing to other mentioned databases.

The basic information in Table 1 characterizes the differences among the selected five databases by the December 2018. The lunar science journals here refer to the ones contain eight research areas including the exploration of the Moon, the evolution of the Moon, the surface analysis of the Moon, the environment of the Moon, the astrophysics of the Moon, the astrochemistry of the Moon, the remote

sensing of the Moon and the comparative planetology. We used research concern to measure whether the database contains enough articles related to lunar science. The research concern is the number of lunar science journals divided by the number of journals contained in a database. The ADS is closely related to lunar science since it's a professional database focusing on astronomy. Although the research concern of Scopus seems low, it has the largest number of lunar science journals. In addition, search results returned from other three comprehensive databases are all covered by the Scopus results. Considering the professionalism of ADS and the comprehensiveness of Scopus, we combined these two databases together to do the bibliometric analysis. The duplicate searched results were removed and the adopted discipline classification was the same as the Scopus'. Extracting data recorded in this comprehensive database in wide coverage avoids introducing bias by missing publications.

2.2 Search strategy

Scientific publications of lunar science constrained to a time span from 1959 to 2018 were extracted from the selected databases on and up to December 31, 2018. Most of the articles about the Moon are published during this time range and their electronic edition could be easily downloaded. Articles from annual Lunar and Planetary Science Conference (LPSC), as well as research articles, review papers, scientific notes and short communications were all considered in this study with their time validity in lunar research. In particular, proceeding articles from LPSC played an important role in lunar science. Although they come from the conference, the form and context were all required as normal research articles did. In addition, articles from LPSC usually represent the newest research results of the lunar science. Thus in this study, journal articles included proceeding articles from LPSC. First, we selected all the articles published during 1959-2018 both in Scopus and ADS. Then, the search arguments 'moon* OR lunar*' were used as the polysemantic keywords to search parts of titles, ab-

stracts, and keywords in Scopus and ADS. In fact, searching is a demanding task. Although the arguments seem consistent, the search engine just recognizes their presence instead of understanding their planetary meaning. Thus, all candidate publications were filtered by subject categories and document types to exclude studies unrelated to the topic.

2.3 Bibliometric analysis

In this study, segmented regression analysis was adopted to the measure ups and downs in the development of lunar science. Six parameters calculated in segmented regression analysis were output volume, keywords, journals, authorship, collaboration, and national output efficiency. They were divided into different segments of growth to characterize the development of lunar science in time series. The model for segmented regression analysis is a nonlinear regression model in exponential form (Eq. 1) and the growth constant is different in each segmented time series. To make the calculation conveniently, the model is log-linearized (Eq. 2) and the coefficients can be estimated with linear regression. The relative growth rate was also used to describe the evolution of publications (Eq. 3) (Bornmann *et al.* 2010; Bornmann and Mutz 2015). Previous researches have testified that three breakpoints in four centuries could explain 99% of the total variance of the annual number of publications (Larsen and Ins 2010). Thus, the time interval from 1959 to 2018 is possible to divide into three segments to clarify the development of lunar science. All the regression analysis in this study were performed in Microsoft Excel and SPSS software.

$$f(t_n) = ae^{bt_n} \quad (1)$$

$$\log(f(t_n)) = k + mt_n \quad (2)$$

$$RGR = (\log(f(t_{n+1})) - \log(f(t_n))) / (t_{n+1} - t_n) \quad (3)$$

where the intercept k equals $f(t_0)$ – the output in the year 1959, $k = \log(f(t_0))$, m is the growth constant, t is the time, n is the time period since 1959. The change $f(t)$ in a period $t_{n+1} - t_n$ is therefore proportional to the status at the starting point in time t_n .

3 Analysis and discussion

3.1 Publication output volume

The overall 49,161 articles of lunar science published during 1959-2018 were accounted for 0.6% of journal articles of the comprehensive database in the same time range. The number of articles of lunar scientific research had experienced an exponentially rapid growth, decline and then continued to increase when the first reference after being published in 1959. In 1977, published articles reached a peak of 1,587. In 2018, published articles were eight times more than that in 1959. Even during the period of decline, published articles were three times more than that in 1959. In this sixty years, the research field of lunar science had expanded from the study of lunar exploration technology and observation of lunar surface, to the study of manned lunar landing technology, inner structure of the moon, evolution of the Earth-Moon system, and even evolution of the entire solar system.

The number of publications clearly indicated that the evolution of lunar science could be divided into three stages that closely related to exploratory activities of the Moon. In the Cold War-inspired space race between the Soviet Union and the United States of America (USA) from 1959-1977, the publications grew in a perfect log-linearized model with the R^2 reach to 0.967 (Figure 2). This stage was characterized by a relatively high growth rate of 6%. The peak number 1587 appeared in 1977 and it was also the largest annual publication number during the past sixty years of the lunar research. In 1959, the first spacecraft Soviet Union Luna 2 impacted the lunar surface on the 13th September and Luna 3, in October that same year, which completed the first flyby of the Moon and obtained the first ever images of the far-side of the Moon. In the next two years, the USA started the impressive Apollo program consuming almost 4% of the US federal budget (at the peak of its development phase) that landed human beings on the Moon and took 382 kg of rock and soil samples back to the Earth (Crawford *et al.* 2014). These incredible scientific legacies provided significant data for researchers to inspect our nearest neighbour in the solar system and to address a couple of questions about the Moon's formation, evolution, resources potential, and wider solar system processes (Isaacson *et al.* 2011).

Then, the lunar exploration came to a long silent stage (1978-1996) with the end of Apollo program (in 1972) and the Soviet mission to the Moon (Luna 24 in 1976). The number of publications about the Moon decreased following a weak log-linearized model (Figure 2) and reached the lowest point in 1996 with only 397 articles published. The low growth

rate of -0.9% suggested that the declination of publication wasn't obvious, even the total number of publications during this period was the largest comparing the other two stages. This kind of decreasing tendency had a time lag so that the production gap didn't appear until twenty years later. At the beginning of the long gap, the publications could still hold the annual productivity of over thousand with the support from the repositated data, national fundings and scientific interests. Around 1990-1992, a small bounce may be caused by the new plan (Clementine) in preparation. With the time passed by, the publications fell sharply since there's no more new data, new techniques or enough budget for continuing lunar research.

The new journey of lunar exploration didn't revive until the late twentieth century when the Clementine and Lunar Prospector were successfully launched. In this stage from 1997 to 2018, other countries and groups in the world includ-

ing China, India, Japan and European Space Agency all declared their plans in lunar exploration including Chang'E, Chandrayaan, SELENE, and SMART-1. The flourishing of lunar missions directly promoted the rapid development of scientific research of the Moon by creating new techniques and providing loads of renewed data. It also attracted more sponsors from different fields including commercial groups or politician communities. Moreover, it benefited the related research areas and provided significant methods for exploring other planets in the solar system. All these discussed above were reflected on the growth of the publications from 406 in 2000 to 1010 in 2018 in a moderate log-linearized model (Figure 2). In this stage, the relative growth rate of 1% was lower than that in the space race time implying the studies on the Moon was on its way to recovering from silent stage.

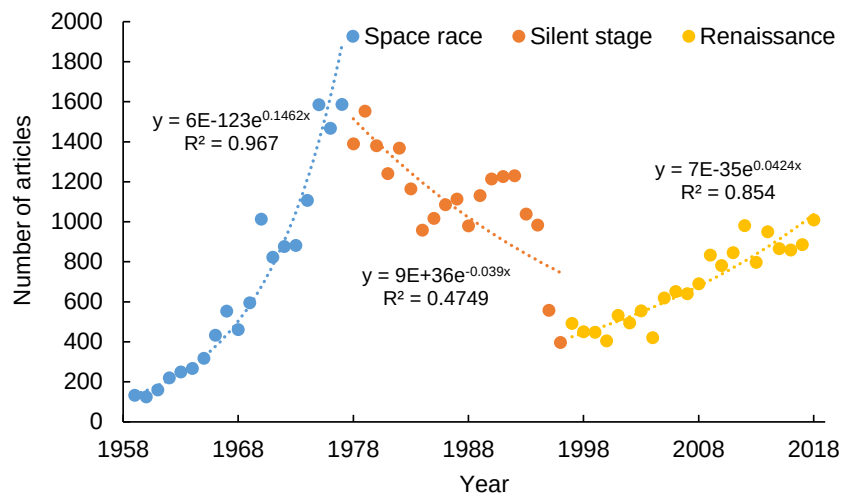


Figure 2. Segmented growth of the annual number of articles. Different colors represent three developing stages of lunar science.

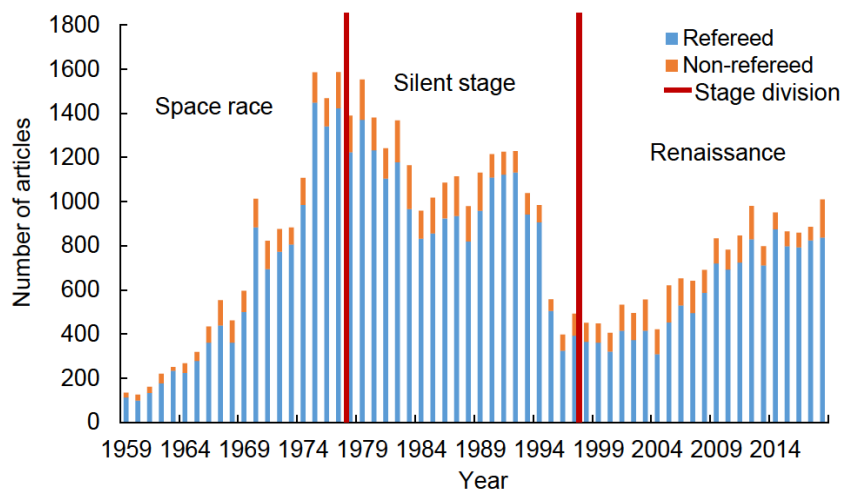


Figure 3. The percentage of refereed and non-refereed articles in three developing stages of lunar science.

(Figure 5). The purple words represented eternal theme when we referred to the lunar research and the other three colours indicated keywords occupied relative important positions comparing to other keywords in different developing stages. Lunar, astronomy and planet were the most common words when we talked about the Moon, as well as space vehicle, Earth, crater and origin. Although the latter four words didn't appear as many as Moon, astronomy, planet or lunar did, they were always the research points in all stages of the evolution of lunar science. It isn't difficult to understand that the lunar exploration need space vehicle and scientists' final aim is to depict what the moon

originally looks like. As for the impact crater is the typical geomorphological units on nearly every corner of the lunar surface, it doesn't only serve as the window for penetrating the inside of the Moon, but also play a significant role in the comparative study of other planets including Mars, Mercury and our Earth. From these seven marked keywords, the well-developed disciplines of lunar science could be listed: astronomy, space engineering, earth and planetary science. The green keywords represented research interests in the space race stage. Considering the most legacies during this period were returned lunar samples and Moon-landed human beings, publications cared about the research around

Table 2. Journals related to lunar science with total publications more than 50 in three developing stages.

Rank	Journals	Space Race (1959-1977)	Silent Stage (1978-1996)	Renaissance (1997-2018)	Sum	Impact Factor (5 years)
1	Journal of Geophysical Research	766	2122	1061	3949	4.180*
2	Icarus	734	2037	1022	3793	3.427
3	LPSC	1604	1371	126	3101	
4	Nature	613	699	441	1753	45.819
5	Science	631	596	212	1439	43.655
6	Geophysical Research Letters	111	798	485	1394	4.909
7	Earth, Moon and Planets	639	551	153	1343	0.71
8	Geochimica et Cosmochimica Acta	224	791	283	1298	5.002
9	Advances In Space Research		587	634	1221	1.7
10	Earth and Planetary Science Letters	382	416	259	1057	5.164
11	Planetary and Space Science	148	229	538	915	1.956
12	Astrophysical Journal	218	353	305	876	5.534
13	Sky and Telescope	208	243	359	810	-
14	Acta Astronautica	13	186	505	704	2.309
15	Astronomy Reports	420	203	30	653	0.949
16	Astronomicheskii Vestnik	172	442	-	614	-
17	Astronomy and Astrophysics	91	278	231	600	5.379
18	Astronomical Journal	285	175	129	589	4.952
19	Kosmicheskie Issledovaniia	178	301	-	479	-
20	Monthly Notices of The Royal Astronomical Society	75	70	195	340	4.986
21	Meteoritics and Planetary Science	0	25	282	307	2.549
22	Solar System Research	71	46	149	266	0.893
23	Astrophysical Journal Letters	75	112	78	265	6.435
24	Space Science Reviews	57	53	149	259	8.156
25	Astronomicheskii Zhurnal	202	57	-	259	-
26	Doklady Akademii Nauk Sssr	92	157	-	249	-
27	Physics of the Earth and Planetary Interiors	93	92	44	229	2.573
28	Cosmic Research	132	35	61	228	0.678
29	Celestial Mechanics and Dynamical Astronomy		59	167	226	1.845
30	Philosophical Transactions of the Royal Society B-Biological Sciences	134	57	26	217	7.205
31	Astrophysics and Space Science	53	49	93	195	1.491
32	Journal of Spacecraft and Rockets	78	35	52	165	1.21
33	Astronomy and Geophysics	-	-	86	86	0.332
34	Earth, Planets and Space	-	-	80	80	2.507
35	Journal for the History of Astronomy	-	-	70	70	0.435
36	Astrobiology	-	-	65	65	3.79
37	Geology	-	-	55	55	5.406

*The impact factor of Journal of Geophysics Research: Planets

these two topics including astrochemistry, samples and lunar mission. Also, some astrophysical words appeared more in this stage suggesting some basic physics studies had done for the mechanism of the lunar research. Hence, astrochemistry and astrophysics mainly developed during this period. The orange keywords concentrated in the silent stage when scientists used the data and samples from space race stage to do further research on the Moon and publications involved in areas including geology, geomorphology, mineralogy and meteorology. The blue keywords could be named as technical words indicating the fast developing techniques in the stage of renaissance. Spectroscopic, photometric and remote sensing in bigger size pinpointed that the growing well-designed satellites delivered big data to assist researchers in method exploring rather than theoretical study. Therefore, data analysis and model simulation was largely adopted to trace the historical evolution of the Moon. The extracted keywords reflected the eight aspects of lunar science listed in section 1 and emphasized in different stages.

Table 2 listed the journals which had published over 50 articles in the different stages of lunar exploration. There was only one journal with Moon in her journal title ranking seventh in publishing. 60% of the TOP 10 journals belonged to the discipline of geosciences or multidiscipline instead of astronomy. The impact factor of journals ranged from 0.32 to 44.96 distributed evenly and the average impact factor was 3.14 excluding Science and Nature. Comparing to renowned *Icarus*, the *Journal of Geophysical Research* ranked first in this ranking list since it had four sub-issues (planets, solid earth, earth surface and space physics) for researchers to submit. As for the lunar exploration represented the most advanced scientific and technological development, the breakthrough in the lunar study were favored by state-of-the-art journals: Nature and Science. The proceeding articles from LPSC and non-refereed articles from the Sky and Telescope ranked top 20, which suggested that conferences and science education held a vital role in lunar science.

In the space race stage, four journals (*Astronomicheskii Zhurnal*, *Astronomicheskii Vestnik*, *Kosmicheskie Issledovaniia*, *Doklady Akademii Nauk SSSR*) from Russia (present) contributed 644 articles, which were even doubled in the silent stage. However, they had no more Russian publications in the renaissance stage and change to English journals facilitating scientific communication. Comparatively, some journals sprang up in the renaissance stage including *Astronomy and Geophysics*, *Earth, Planets and Space*, *Journal for The History of Astronomy*, *Astrobiology*, *Geology*. *Astronomy and Geophysics* published short review papers on subjects within the remit of the Royal Astronom-

ical Society since 2012, while the other four journals were representatives from categories of geology, philosophy and biology. It implied that research points were broadened in other intersected scientific areas with booming techniques in the past twenty years. Some journals from categories of engineering, materials and remote sensing weren't listed here just because of less than 50 articles concerning the Moon were published, however, they displayed more interests in incorporating articles about the lunar study. In short, articles of lunar science declined in comprehensive journals while rolled up in professional journals. Similarly, articles of lunar science gradually transferred from traditional journals in lower publication frequency to relative new journals in higher publication frequency. These two demonstrated that lunar science developed in a professional and quality-assured manner.

3.3 Authorship

It's an effective way to grasp the base of a research point or handle a research method systematically by following a leader in one research area through their academic publications. In Figure 6(a), the author network displayed the top 200 authors, who were the representatives of the corresponding research areas of lunar science. These research areas had no strict boundaries for the authors since many scientists made outstanding contributions in more than one area. Each biggest bold name in every area is the leading researcher in this field, who has collaborated with other researchers all over the world and published articles that were highly cited. No matter from article production or collaboration (both in the first place), James W. Head is the captain of the study of the Moon (Figure 6(b)). He and his collaborators focused on but limited to studying the evolutionary process of the Moon, which was the most active research area of lunar science in the past forty years. Mark S. Robinson is another prolific researcher studying the Moon mainly from the perspective of remote sensing, as well as collaborating with authors in many other areas including surface analysis, geochemistry and evolutionary process. For the authors in the area of the geochemistry, their collaboration evenly distributed in the rest research areas since their work provided basic chemical, physical and geologic information for advanced lunar research.

Moving on now to consider multiple authorship among article in lunar science. The Figure 7(a) illustrated that scientists had become increasingly collaborative over the past 60 years. The fraction of single-author papers dropped in a 29% rate since 1959, albeit it was the principal part of the authorship. Both double-author and triple-author papers

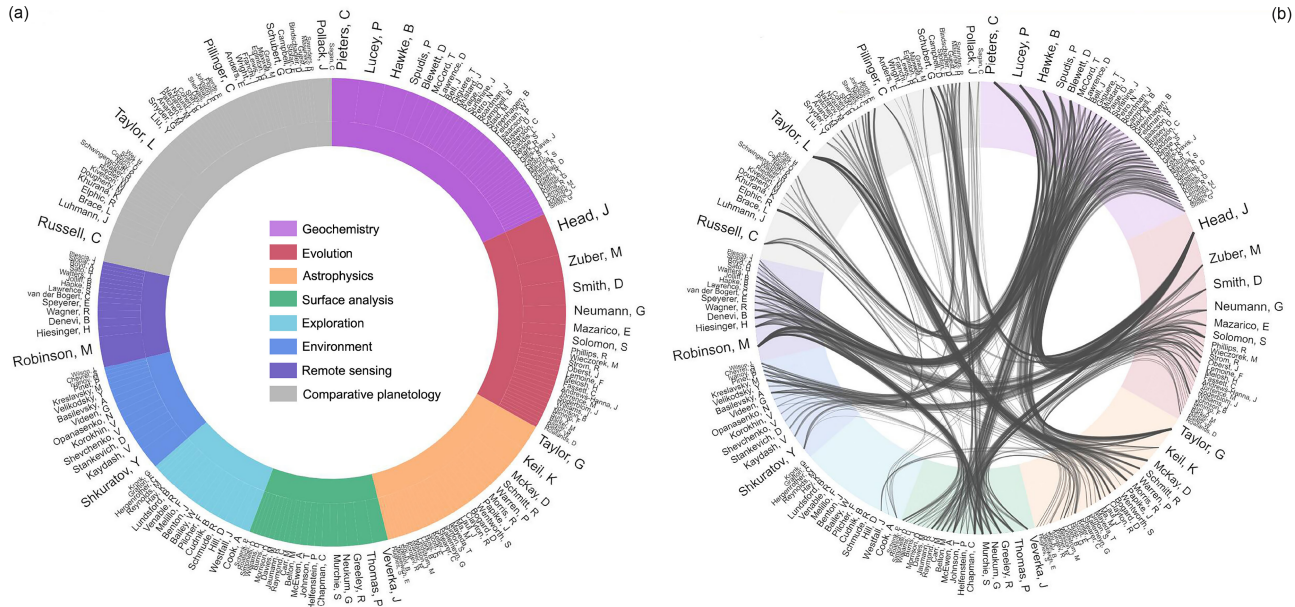


Figure 6. (a) Representative scientists in different research areas. The bolder the name is, the more publications the author has. (b) The academic links among authors in different research areas. The bolder the line is, the more collaborative the author is.

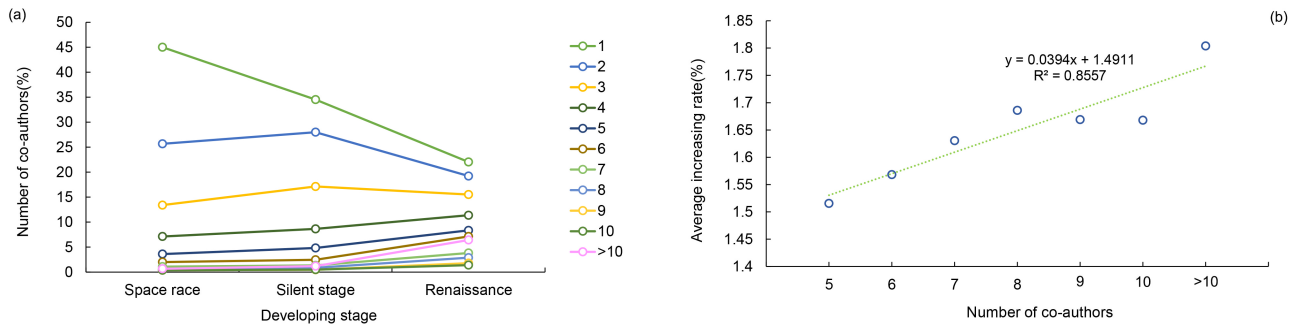


Figure 7. (a) The percentage of the number of co-authors in three developing stages. Authors become increasingly collaborative in the past sixty years. (b) The publications with more than five authors increased in a log-linearized model.

went through a maximum in silent stage and then levelled off, while four authors collaboration predominated with an increasing rate of 20%. The average increasing rate of publications with more than 5 authors reached 45% and increased in a log-linearized model (Figure 7(b)). In particular, publications with more than ten authors in the renaissance stage were nearly four times to that in the silent stage.

Several factors are known to be associated with trends in multiple authorship in lunar science. The key factor is the multidisciplinary nature of lunar science determining by research data, methods and techniques related to joint scientific fields. For example, the limited amount of time available on spacecraft observatories motivates astronomers to form larger teams to collect rock samples. Numerical simulations operating on supercomputers requires groups of programmers or data scientists to design, filter, analyze and

visualize big data. Another significant factor is the global increase in the number of researchers in lunar science. The membership of the American Astronomical Society nearly tripled from 2619 (in 1970) to 6800 (in 1996), while that of the International Astronomical Union was a 1.3 times increase from 2003 to 2015 (Smith 2016). In addition, lunar/planetary exploration becomes an important part in national development plans, which will promote potential international collaborations.

3.4 Collaboration

Multiple collaboration refers to collaboration among multiple authors from different research institutions in the same country. In this part, the collaboration was measured by extracting affiliations of authors from all the searched pub-

lications. For the authors who worked in more than one institute, we chose the first one as his/her affiliation to complete this analysis. The percentage of multi-institutional publications was only 4% during the space race period and increased rapidly to approximately 28% in the silent stage, finally reached 52% during the renaissance period, which suggested a distinct increase in scientific collaboration in the field of lunar science. The USA taking 25% of all cooperative relationship was the center of the collaboration and 26% of her international collaborations were with Germany. Germany and France accounted for 11% and 10% of the collaboration respectively while that of rest countries were below 8% (Figure 8). Although Russia published more articles about the Moon compared to Germany and France, its lunar research was mostly done by researchers in the same institution. However, in term of collaboration proportion, the result was in contrast. The average multi-collaboration

proportion was 58% and the average international collaboration proportion was 39%. European Union Countries were more collaborative both in multiple and international collaboration in comparison with USA, Russia, Canada and other European countries (Figure 9). Japan and China were two active Asian countries in scientific collaboration while Indian's collaborative research was below the average level.

For the USA and Russia, the percentage of collaboration was lower than some European Union Countries may result from their prominent position in the earlier stages of the lunar study. In addition, lunar explorations motivating by European Union itself provided a convenient platform for scientists' from European Union Countries to have scientific communication. The international cooperation of some Asian countries was also in high percentage since their lunar exploration programs started relatively late and they were actively looking for scientific partners from foreign countries.

We also examined the collaboration among top-24 international research institutions defining by their publication output (Figure 10). Two-thirds of these top institutions belonged to the USA. Undoubtedly, NASA was the leading organization guiding the development of lunar research compared to other national institutions. 48% of collaboration was among American universities with NASA while 25% of that was among foreign research institutions and NASA. NASA has several field centers owing their strengths, which have assisted in multiple collaboration in various disciplines relating to different international institutions. French National Center for Scientific Research was the representative institution in lunar research from the European Union Country. Japan Aerospace Exploration Agency, Imperial College London and Italian National Institute for Astrophysics were the three most open research institutions in term of collaboration proportion though their publication output was much less than NASA. Japan also was the only country had two institutions in this top-24 list except USA. NASA was the representative of the lunar research institution, while California Institute of Technology was the leader of the university system for the study of the Moon focusing on the astrophysical study of the Moon. Other universities had their preponderant research points, such as Brown University focused on lunar surface analysis and evolution, while Arizona State University cared about remote sensing data processing and analysis.

Active scientific collaboration with important institutions faces fierce competition. Important institutions such as NASA represents more publications, higher-quality research and more interinstitutional collaboration links. They have already accumulated abundant resources and achievement. Ordinary institutions, especially new institutions

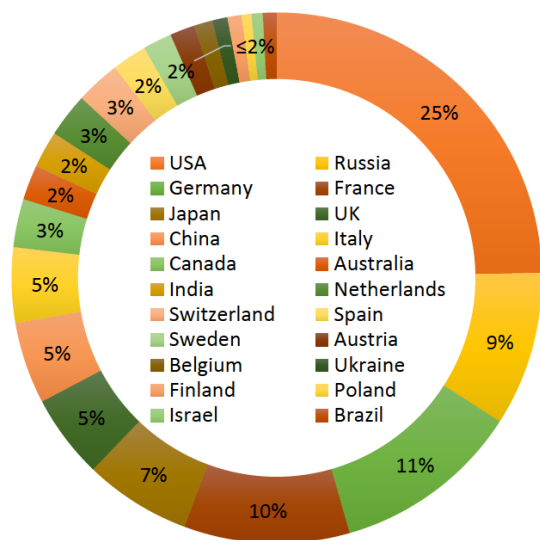


Figure 8. The percentage of multiple collaboration in different countries.

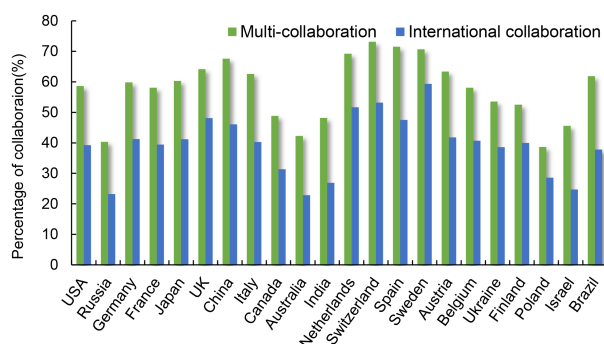


Figure 9. The percentage of multi-collaboration and international collaboration of each country.



Figure 10. The word cloud of top 24 research institutions from different countries. The larger the word, the more active the institution in the collaborative cloud. Different colours represent the institutions from different countries. The former percent in the legend is the average multi-collaboration percentage and the latter is the average international collaboration percentage.

could get the brand effect from important institutions by constructing collaboration links with them and develop research and expand academic reputation. In other words, the alliance between giants could expand collaborative effect that motivates the development of lunar science.

3.5 National output efficiency

The national output efficiency was measured by analyzing the relationship between the average annual GDP and average annual number of publications from each country. The GDP data came from 26 countries with the average annual publication output more than 1 from 1959 to 2018.

On average, countries in the world concerning the lunar exploration had a four-times growth in the number of published papers in per 20-year interval. Countries with the average annual GDP over 4,000 billion dollars published over 22 papers per year while countries with the average annual GDP less than 3,000 billion dollars published less than 5 per year. According to the simple linear regression analysis (Figure 11(a)), the number of publications correlated strongly with GDP in the stages of space race and renaissance as the R^2 was bigger 0.9 and the significant F value was near to zero. In general, the higher the GDP, the more the publication output of the lunar research. The slope of the fitting line of space race stage was larger than that of renaissance stage indicating that a large part of

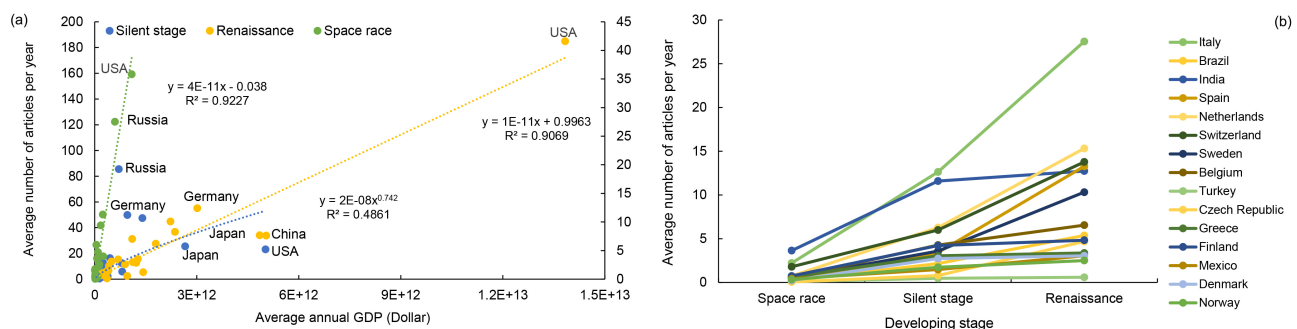


Figure 11. (a) The linear correlation between average number of articles per year and average annual GDP of the countries across the world in three developing stages. (b) The relationship between average number of articles per year and average annual GDP of the countries in low annual GDP clustered in the left bottom of Figure 11 (a). The X-axis represents average annual GDP increases from the space race stage to the renaissance stage.

the national finance was devoted to the development of aerospace industry, especially for the USA and Russia. The USA stood out with high GDP and publications since, as discussed in the previous sections, the USA was the center of international scientific collaboration and had multiple important research institutions involving every aspect of lunar science. After 20-year hiatus in lunar missions, both increasing GDP and a renaissance in lunar exploration all over the world shaped a relative moderate growth comparing to that in the space race stage. In the silent stage, the relationship between average annual GDP and average annual publication output didn't follow an obvious regression model. Russia had the highest annual publication output though her annual GDP only ranked in the seventh place, whereas the annual publication output of the USA drooped to 23 though her annual GDP still in the first place. During this period, most of the countries funded other industries instead of aerospace programs to strengthen their nations with the space race faded. Because of the regime change, Russia (its legal successor state) experienced a slow development in lunar exploration comparing to other countries in the renaissance stage. On the contrary, countries including Italy, Brazil, Spain, Netherlands and Switzerland had made remarkable progress in lunar scientific research in the renaissance stage (Figure 11(b)). On the basis of earnest work of European Space Agency, these countries had become increasingly active in lunar research from space race period to renaissance period. Germany steadily support the lunar research considering her annual GDP in the past sixty years. For UK and France, their publications reached one-fourth of USA respectively with lower GDP than China and Japan. China was the Asian country with the fastest growth in GDP and articles during the Renaissance, followed by Japan. With adequate financial support, Asian countries including China, Japan and India had launched a serious of spacecraft boarded new instruments to focus on lunar exploration. As deep space exploration becomes the focus of the world, GDP and related policy will be an informative indicator to forecast the frequency of lunar exploration.

3.6 Future outlook

According to the above bibliometric analysis of the publications about the Moon, future lunar science can be addressed in three categories: 1) The investigation of three stages of lunar science has shown that continuous updating of technology has promoted the vigorous development of lunar exploration. In the future, countries all over the world are suggested to actively cooperate to share mature technologies, save exploration costs, jointly develop new

technologies, accelerate the deep exploration of the moon, provide a paradigm for the exploration of other celestial bodies, and advance the technological update of exploring the solar system; 2) Engineers and scientists will not only care about observing the surface of the Moon, but also apply geophysical technology to detect the inner structure of the Moon. Extensive use of robotic sample return will solve the problem of lacking ground-truth data in lunar research. Scholars would like to expand the scope of research around the establishment of eternal lunar base and space station for human beings, which will promote studies of life sciences, human physiology, astrobiology, and material science. The popularization of lunar exploration will also play important role in lunar science since public attention will provide economic assistance for developing deep space exploration; 3) The findings of this study suggest that it's useful to build open platforms for providing data standards, data processing methods, and data products on the basis of high-performance computing network to promote the sharing of lunar exploration technology and research results on the global scale. These open platforms will assist in establishing research paradigm in multiple fields of lunar science and continuously expanding new lunar scientific research, which is beneficial to providing comprehensive technology, information and service support for solar system exploration.

4 Conclusion

The aim of the paper is to examine the development of lunar science by analyzing the scientific publications about the Moon from a bibliometric perspective. The development of lunar science experienced rise and fall corresponding to a log-linearized model that could be clearly divided into three stages: space race, silent stage and renaissance. Keywords extracted from publications as reliable predictors of multidiscipline showed that the well-developed disciplines of lunar science were astronomy, space engineering, earth and planetary science, while other disciplines played important roles in different stages. Journal of Geophysical Research issues with higher impact factors were the comprehensive journals that scientists preferred to publish their research results, while *Icarus* was the most popular professional journal for researchers to choose. Researchers had become cooperative rather than independent in publishing in the past sixty years. Countries with higher average annual GDP contributed more to the development of lunar science.

After telescopic observations over the centuries, space technology made lunar exploration possible to conduct ob-

servations from lunar orbit, make in situ measurements on the lunar surface, collect rock samples for analysis in terrestrial laboratories, and make human exploration of the Moon more significant. Spectral studies by remote sensing from orbiting spacecraft of the Moon initially aimed to the simple reconnaissance of unknown surfaces, while the early history of the solar system, the geological evolution of rocky planets, and the near-Earth cosmic environment throughout solar system history increasingly attract scholars' attention. Correspondingly, astronomy, astrobiology, fundamental physics, life sciences, and human physiology will have increasing opportunities to intersect with lunar scientific studies. The findings from this work will be of interest to scientists who want to realize the history of lunar science in a quantitative view, detect multidisciplinary and appropriate journals for the lunar research publishing, and find outstanding institutions that have open collaborative systems and sufficient financial support to share research data and improve research efficiency.

Conflict of Interest: The authors declare that they have no conflict of interest.

Data Availability Statement: The bibliographic and other material used in this study is available from electronic literature databases via the World Wide Web.

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References

- Archambault E, Campbell D, Gingras Y, Larivière V. 2009. Comparing bibliometric statistics obtained from the Web of Science and Scopus. *J AM SOC INF SCI TEC*. 60(7):1320–1326.
- Baker VR. 2015. Planetary geomorphology: some historical/analytical perspectives. *Geomorphology*. 240:8–17.
- Barbosa SDJ, Silveira MS, Gasparini I. 2017. What publications meta-data tell us about the evolution of a scientific community: the case of the Brazilian Human–Computer Interaction conference series. *Scientometrics*. 110(1):275–300.
- Bordons M, Aparicio J, Costas R. 2013. Heterogeneity of collaboration and its relationship with research impact in a biomedical field. *Scientometrics*. 96(2):443–466.
- Borgman CL, Furner J. 2002. Scholarly communication and bibliometrics. *ANNU REV INFORM SCI*. 36:3–72.
- Bornmann L. 2015. Alternative metrics in scientometrics: a meta-analysis of research into three altmetrics. *Scientometrics*. 103(3):1123–1144.
- Bornmann L, Mutz R. 2015. Growth rates of modern science: A bibliometric analysis based on the number of publications and cited references. *J ASSOC INF SCI TECH*. 66(11):2215–2222.
- Bornmann L, Mutz R, Daniel HD. 2010. The h index research output measurement: two approaches to enhance its accuracy. *J INFORMETR*. 4(3):407–414.
- Broadus RN. 1987. Toward a definition of “bibliometrics”. *Scientometrics*. 12(5-6):373–379.
- Chang CC, Ho YS. 2010. Bibliometric analysis of financial crisis research. *AFR J BUS MANAGE*. 4(18):3898–3910.
- Correia A, Paredes H, Fonseca B. 2018. Scientometric analysis of scientific publications in CSCW. *Scientometrics*. 114(1):31–89.
- Crawford IA, Joy KH, Anand M. Lunar Exploration. 2014. In: Spohn T, Johnson TV, Breuer D, editors. *The Encyclopedia of the Solar System*. 3rd ed. Boston: Elsevier; p. 555–579.
- Gu YN. 2004. Global knowledge management research: A bibliometric analysis. *Scientometrics*. 61(2):171–190.
- Hearnshaw J. 2006. A survey of published astronomical outputs of countries from 1976 to 2005 and the dependence of output on population, number of IAU members and gross domestic product. *Proceedings of the International Astronomical Union*. 2(SPS5):9–20.
- Piégay H, Kondolf GM, Minear JT, Vaudor L. 2015. Trends in publications in fluvial geomorphology over two decades: A truly new era in the discipline owing to recent technological revolution? *Geomorphology*. 248:489–500.
- Inglesi-Lotz R, Balcilar M, Gupta R. 2014. Time-varying causality between research output and economic growth in US. *Scientometrics*. 100(1):203–216.
- Isaacson PJ, Sarbadhikari AB, Pieters CM, Klima RL, Hiroi T, Liu Y, et al. The lunar rock and mineral characterization consortium: deconstruction and integrated mineralogical, petrologic, and spectroscopic analyses of mare basalts. *Meteorit Planet Sci*. 2011;46(2):228–251.
- Kurtz MJ, Eichhorn G, Accomazzi A, Grant C, Demleitner M, Murray SS. 2005. Worldwide use and impact of the NASA Astrophysics Data System digital library. *J AM SOC INF SCI TEC*. 56(1):36–45.
- Kurtz MJ, Eichhorn G, Accomazzi A, Grant CS, Murray SS, et al. 2000. The NASA Astrophysics Data System: overview. *ASTRON ASTROPHYS SUP*. 143(1):41–59.
- Larsen PO, von Ins M. 2010. The rate of growth in scientific publication and the decline in coverage provided by Science Citation Index. *Scientometrics*. 84(3):575–603.
- Liu FL, Lin AW, Wang HH, Peng YL, Hong S. 2016. Global research trends of geographical information system from 1961 to 2010: a bibliometric analysis. *Scientometrics*. 106(2):751–768.
- Maisonobe M, Grossetti M, Milard B, Jegou L, Eckert D. 2017. The global geography of scientific visibility: a deconcentration process (1999–2011). *Scientometrics*. 113(1):479–493.
- Mingers J, Leydesdorff L. 2015. A review of theory and practice in scientometrics. *Eur. J. Oper. Res*. 246(1):1–19.
- Peng Y, Lin AW, Wang K, Liu FL, Zeng F, Yang L. 2015. Global trends in DEM-related research from 1994 to 2013: a bibliometric analysis. *Scientometrics*. 105(1):347–366.

- Serenko A, Bontis N, Booker L, Sadeddin K, Hardie T. 2010. A scientometric analysis of knowledge management and intellectual capital academic literature (1994-2008). *J KNOWL MANAG.* 14(1):3–23.
- Smith GH. 2016. Trends in Multiple Authorship among Papers in Astronomy. *PASP.* 128(970):124502.
- Sooryamoorthy R. 2018. The production of science in Africa: an analysis of publications in the science disciplines, 2000–2015. *Scientometrics.* 115(1):317–349.
- Tian YG, Wen C, Hong S. 2008. Global scientific production on GIS research by bibliometric analysis from 1997 to 2006. *J INFORMETR.* 2(1):65–74.
- van Bochove CA. 2013. Economic statistics and scientometrics. *Scientometrics.* 96(3):799–818.
- Wang JY, Liu ZG. 2014. A bibliometric analysis on rural studies in human geography and related disciplines. *Scientometrics.* 101(1):39–59.
- White JC. 1992. Publication Rates and Trends in International Collaborations for Astronomers in Developing Countries, Eastern European Countries, and the Former Soviet Union. *PASP.* 104(676):472–476.
- Winnink JJ, Tijssen RJW. 2014. R&D Dynamics and scientific breakthroughs in HIV/AIDS drugs development: the case of Integrase Inhibitors. *Scientometrics.* 101(1):1–16.