Review Article

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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; Maisonobe 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-
muninist 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. Hearmshaw (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 including 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               |

Table 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 professionality 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-
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 reposed 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 including China, India, Japan and European Space Agency all declared their plans in lunar exploration including Chang’E, Chandrayaan, SELENE, and SMART-1. The flourishment 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.](image)

![Figure 3. The percentage of refereed and non-refereed articles in three developing stages of lunar science.](image)
Apart from regression analysis, the publications were also discriminated as refereed or non-refereed to estimate the quality of publications. On average, the non-refereed publications occupied 15% of all the publications, which implied 85% of the publications were peer-reviewed to release academic achievements in a scientific way (Figure 3). For lunar science, however, this 15% weighed greatly since the popular science education and some special-interest research areas needed them to broadcast scientific information.

According to the analysis of the total number of articles in past 60 years related to highlights of lunar exploration by spacecraft, it was found that the Apollo series had the most outputs, followed by the Luna series, the Chang’e series ranked third, and the Surveyor series ranked fourth. From the point of view of single mission, Apollo 11 published the most to 6,300 articles, Apollo 15 followed closely, and Lunar Orbiter 5 had the least amount of 87 articles. Apollo11-17 published more than 4000 articles, and both Clementine and LRO published more than 3800 articles, which was the largest number of outputs except Apollo’s single mission. The number of the articles was closely related to the designed content of lunar missions. The first manned mission to the Moon completed by Apollo 11, which had the most published articles, had expanded the research from orbital observations to in-situ experiments, sample analysis, construction of Moon base, astrochemistry, etc. Apollo15 refined researches of lunar environment and applications of remote sensing and ranked second in publishing because of carrying a lunar rover for the first time. As the earliest lunar mission successfully launched, the Luna series provided a solid foundation for lunar exploration research. As the most successful lunar mission in Asia, the Chang’e series covered the core missions of lunar exploration in a short time and the number of articles were at the forefront (Figure 4).

### 3.2 Keywords and journals

Keywords define the field, subfield, topic and research issue that is covered by the article (Correia et al. 2018). Thus, it’s important to dig out the research concerns related to the Moon as well as by searching relevant keywords. The keywords were screened out in form of word cloud in which the bigger the word, the higher the appearing frequency.

![Figure 5. The word cloud of keywords. The size of each word represents the frequency that appears in the extracted articles. The colors represent developing stage of lunar science: the purples words are dominant all the time; the green words appear mostly in space race time; the orange words appear mostly in the silent stage; the blue words appear mostly in the renaissance stage.](image-url)
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 | 4.090                   |
| 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 physic 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 (AstronomicheskiiZhurnal, Astronomy, Kosmicheski Izvedovaniia, 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 Astronomical 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
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-
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 reaching 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
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...
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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