The Global Structure of International Scientific Collaborations

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Abstract
While there is a consensus that there is a core-periphery structure in the global scientific enterprise, there have not been many methodologies developed for identifying this structure. This paper develops a methodology by looking at the differences in the power-law structure of article outputs and degree distributions of countries and applies the method to five different scientific fields: astronomy & astrophysics, energy & fuels, nanotechnology & nanosciences, nutrition, and oceanography. The analysis highlights differences in the structures of these fields and their impact on citation behaviour.

Introduction
There is a hierarchical, core-periphery structure in science that has dominated the international relations for scientific cooperation throughout the 20th century (Ben-David 1971, Traweek 1988, Schott 1998, Hwang 2008). Historically, the core structure was composed of the United States, Japan and the Europe Union (Ohmae 1985, Glänzel et al 2008). Socio-cultural elements such as nationality, colonial past, scientific heritage, and infrastructure reinforced the core-periphery structure (Oldham 2005, Hwang 2008). This structure predetermined the status of scientists and institutions creating a disadvantage for countries in the periphery to invest in the human capital necessary to advance their own institutions to be equal to those in the core (Schott 1998, Hwang 2008).
However, this triad and the corresponding core-periphery structure has begun to break down in the 21st century. There has been an exponential growth over the past two decades in international scientific cooperation (ISC) (Glänzel 2001). This cooperation results in the rapid creation of new knowledge and transfer of knowledge across borders. This growth in international cooperation has had profound effects on the conduct of research both internal and external to national borders. These changes in conduct in turn have implications for the effective functioning of national systems supporting science (Hill 2007). New countries, mainly from Asia, have invested heavily in the sciences (Wagner & Leydesdorff 2005, Glänzel et al 2008, Hwang 2008, Leydesdorff & Wagner 2008).
These changes began during the turn of the century and continue to this day. Even as these changes have taken place, there continues to be, as King (2004) put it, “a stark disparity between the first and second division in the scientific impact of nations”. This second division, the developing world, is increasingly becoming marginalized and exploited by those countries in the core (Lall 2001, Oldham 2005).
Yet, the mechanisms and processes that underlie the growth in cooperation at the national level is poorly understood (Katz and Hicks 1997, Wagner-Döbler 2001, Wagner and Leydesdorff 2005). This research in this chapter seeks to contribute our understanding of the underlying structure of the core and periphery through quantitative analysis and understand how it evolves over time. To gain new insights, I will examine ISC networks as an emergent, complex adaptive system.
A characteristic common among emergent systems is that order appears to arise spontaneously from the local interaction of actors who are not necessarily aware of how their actions contribute to the larger order (Holland 1998). Prior research on scientific collaborative networks (Newman 2001, 2004, Barabasi et al 2002, Wagner and Leydesdorff 2005 among others) has shown that collaborative networks are emergent, complex adaptive systems. This

research will extend the work of these scholars to a macro study of collaboration among nation-states.

Data Collection and Methodology

Data was drawn from Thomson Reuter's ISI online bibliometrics database, Web of Knowledge (WoK) and the country names were standardized.[34] WoK is one of the most comprehensive databases of peer-reviewed journals covering over 256 subjects dating back 100 years. Each subject area has a group of corresponding group of journals that provide a broad coverage on related topics. To provide a wide breadth for analysis, five subject areas were chosen: Astronomy and Astrophysics, Oceanography, Energy and Fuels, Nanosciences and Nanotechnology, and Nutrition. The first two subjects are representative of the basic sciences; the next two are applied sciences and the last draws from medicine. Statistics for these fields are shown in Table 1.

Table 13 Subject Area Statistics[35]

Field	Coverage	Journals	Articles	Avg. Citation
Astronomy	1979-2008	54	228796	24.3
Energy	1978-2008	74	88886	7.7
Nanotech	1981-2007	47	74755	7.5
Nutrition	1979-2008	69	95350	16.2
Oceanography	1979-2008	57	64764	18.8

To conduct this analysis, abstracts from all journals associated with the selected fields were downloaded and parsed into a database for analysis using customized software. Only research articles were analyzed, conference proceedings, reviews, editorials and letters were ignored. The number of research articles reported in Table 1 includes only articles with author address information included. With the exception of Energy and Fuels, less than 2.5% of articles did not have address information. For energy and fuels, slightly less than 12% of articles did not contain author information.[36]

For longitudinal panel analysis, publications were split into 3 major time periods: 1978-1992, 1993-2000, and 2001-2008. The first time period represents the global polarity in the world between the USSR and USA. The second time period was chosen as it is widely recognized that an explosive growth in international scientific publications followed the post-Soviet time period (Georghiou, 1998; Glänzel, 2001), and the last time period is the current state of field.

Bilateral ties are counted for any instance in which authors from two countries were in the same publication. For articles with authors from more than two countries, each country was counted as country-pairs. For example, for an article with authors from three countries, the article was counted three times, once as a collaboration between country A and country B, then between country B and country C, and finally between country A and country C. This results in countries having more bilateral ties than the total number of articles. To compensate for this, the percentages of articles that are part of an international scientific collaboration (ISC) are calculated as 1 minus the ratio of NumNatlPapers and ArticleCount. The three network centrality measurements (degree, closeness and betweenness) were calculated using UCINET with all edges symmetrized and weighted by the total count of articles.

[34] England, Wales, and Scotland are treated as separate entities in WoS and were combined into the United Kingdom. Additionally, East and West Germany were combined into a single entity prior to 1989.

[35] Nanotechnology & Nanoscience's coverage is shorter than others as the first journal classified in this subject area started at 1981. Additionally, 2008 data was not available at the time data collection occurred.

[36] The cause for this discrepancy was not investigated. However, the author hypothesizes that part of this discrepancy may come from the fact that WoS includes a large number of professional journals.

Power Law Analysis Methodology

A persistent pattern associated with complex system is power laws. In bibliometrics, power laws are commonly seen in publication frequencies (Lotka 1924), citation frequencies (de Solla 1965), the degree of authors in coauthorship networks (Newman 2001, Jeong et al. 2001, Barabassi et al. 2002) and the degree of international coauthorship (Wagner and Leydesdorff 2005).

The majority of analysis used for this paper is based on log-CCDF (Complementary Cumulative Distribution Function) power law which takes the form (Cioffi-Revilla, forthcoming):

$$\log[1 - \Phi(x)] = a' - (b-1)\log x \qquad \text{(Eq. 1)}$$

which yields a C.D.F.

$$\Phi(x) = 1 - ax^{1-b} \qquad \text{(Eq. 2)}$$

and a corresponding probability density function (PDF)

$$p(x) = \frac{a(b-1)}{x^b} \qquad \text{(Eq. 3)}$$

This type of a power law is the same type seen in coauthorship networks and citation networks. In order to determine the power law coefficients, data will be fit into a log-log format seen in equation 1 and then OLS regression will be used to compute the coefficients. A combination of the t-statistic and standard error associated with the power law exponent as well as the R^2 will be used to determine the goodness-of-fit to the power law (Cioffi-Revilla, forthcoming).

Core-Periphery Analysis Methodology

Core-periphery structures are often discussed but lack a formal definition (Borgatti & Everret 1999). When discussing the world scientific system, the core is the area which produces the majority of new science and has a high inwardness, while the periphery consumes the knowledge (Schott 1993, 2001, Hwang 2008). Using this definition or ones similar to this, scientometrics has been used to identify the core through the study of citations, publications and coauthorship (Glänzel 2001, Glänzel et al 2008, Wagner & Leydesdorff 2005, Leydesdorff & Wagner 2008, Hwang 2005, 2008).

Barabasi et al. (2002) found that in some coauthorship networks, a two-tier structure in the degree distribution appears with a cross-over point that varies by discipline. Each of the tiers has a different power-law coefficient. Wagner & Leydesdorff (2005) found similar two-tier architecture in studying international coauthorship networks. This is two tier architecture was coined by Zhou and Mondragón (2004) study on internet topology as the "rich-club phenomenon." Serrano (2008) extended this to weighted networks and found rich-clubs in air transportation, world trade and coauthorship networks.

This research uses the advances in detecting rich-club phenomenon detailed in Serrano (2008) to determine the core countries in the various fields under study and how they have changed over time. The methodology has been adapted into the following algorithm for computing the different power law coefficients and core-membership:

1. Compute the weighted degree of all nodes
2. Compute the log-CCDF as outlined in the power methodology section
3. Use piece-wise linear regression of log-degree and log-CCDF using a moving threshold to get a best fit for power law coefficients

In some cases piecewise linear regression found more than one best fit, in such cases the value which has the great discontinuity with the prior degree centrality was chosen. For example, in oceanography from 2001-2008, the fit for the core beginning at 425 degree and 652 where very close, however the prior for degree value in was 295 and 546 respectively. Thus the discontinuity is greater at 425, thus the four countries with a degree centrality between 425 and 652 were considered part of the core.

Analysis and Results

To grasp the complex underlying patterns associated with international scientific cooperation (ISC) at the macro level, the analysis is broken down into three components:

1. Field Analysis
2. Core-Periphery Analysis
3. Citation Impact Analysis

Each analysis is done over three distinct time periods over five separate disciplines to insight into the evolving nature of ISC. The results of each of these analyses are interpreted independently within this section.

Field Analysis

Statistical Properties

An analysis of collaboration at the disciplinary level shows that collaboration has grown significantly for the selected five case studies over the past thirty years. The results of this analysis are shown in tables 2 and 3.

Table 14 Field Statistics

Field	Time Period	Total Records	Average Citation	Average Authors	Average Countries	Percent ISC paper
Astronomy & Astrophysics	pre-1992	68076	31.85	1.42	1.15	11.5%
	1993-2000	68026	28.66	2.09	1.42	28.5%
	2001-2008	92694	15.62	3.27	1.8	45.3%
Energy & Fuels	pre-1992	29670	7.98	1.08	1.02	1.4%
	1993-2000	15301	10.63	1.33	1.09	8.3%
	2001-2008	43915	6.52	1.64	1.16	14.1%
Nanotech & Nanosciences	pre-1992	6701	15.91	1.13	1.02	2.5%
	1993-2000	19216	10.23	1.48	1.12	11.5%
	2001-2007	48838	5.28	2.01	1.23	20.0%
Nutrition	pre-1992	31175	20.87	1.38	1.04	3.3%
	1993-2000	24758	20.09	1.83	1.12	9.9%
	2001-2008	39417	10.15	2.53	1.24	18.2%
Oceanography	pre-1992	17672	30.09	1.17	1.04	3.6%
	1993-2000	18733	23.9	1.53	1.16	13.2%
	2001-2008	28359	8.48	2.09	1.33	25.4%

Table 3 shows that there are stark differences in the composition of each field. Astronomy and Astrophysics is the most collaborative of the fields surveyed. While Energy & Fuels, which is arguably the most applied science studied, is the least collaborative. Nutrition is the second most collaborative field surveyed in terms of co-authors yet is fourth in terms of percentage of paper that are collaborated abroad and nearly tied with Nanotech & Nanosciences for average countries. This difference in growth of average authors and countries seen in nutrition shows evidence that increases in coauthorship does not lead directly to similar increases in international collaboration, though the two remain highly correlated. The extent of how collaboration has evolved in these fields can be seen in table 4.

Table 15 Field Growth Rates

Field	Avg. Authors		Avg. Countries		Percent ISC	
	1993-2000	**2001-2008**	**1993-2000**	**2001-2008**	**1993-2000**	**2001-2008**
Astronomy &	47.2%	56.5%	23.5%	26.8%	147.8%	58.9%

Astrophysics						
Energy & Fuels	23.1%	23.3%	6.9%	6.4%	492.9%	69.9%
Nanosciences & Nanotech	31.0%	35.8%	9.8%	9.8%	362.5%	74.4%
Nutrition	32.6%	38.3%	7.7%	10.7%	200.0%	83.8%
Oceanography	30.8%	36.6%	11.5%	14.7%	266.7%	92.4%

The growth in average authors is highly correlated with the pre-existing amount co-authorship. That is, the higher the average of number of authors, the higher the growth rate. This indicates there may exist some type of snowballing phenomena which reflects the changing structure of a field. Thus the more collaborative a field is in general, the more authors choose in the future to coauthor in greater team sizes.

The same pattern does not hold for the average countries collaborating on a paper. Astronomy & astrophysics continues to have the strongest growth rate, making it increasingly more global. Of interest though is the difference in growth between nutrition and oceanography. In the initial time period, pre-1992, these two fields had the same average countries. However, the growth rates diverged with oceanography becoming globalized at a rate much faster than nutrition.

The growth in the percentage of articles in a field that are internationally scientific collaborations (articles that had a minimum of at least 2 authors from different countries) grew rapidly in the 1990s. However, the rate of growth was not sustainable and dropped considerably in the most recent time period. The greatest growth was seen in the fields which had the lowest rate of collaboration to start with. The smallest growth came in astronomy & astrophysics, which was the field that already had the highest level of collaboration. The difference of growth rates between nutrition and oceanography followed a pattern similar to that seen the average countries.

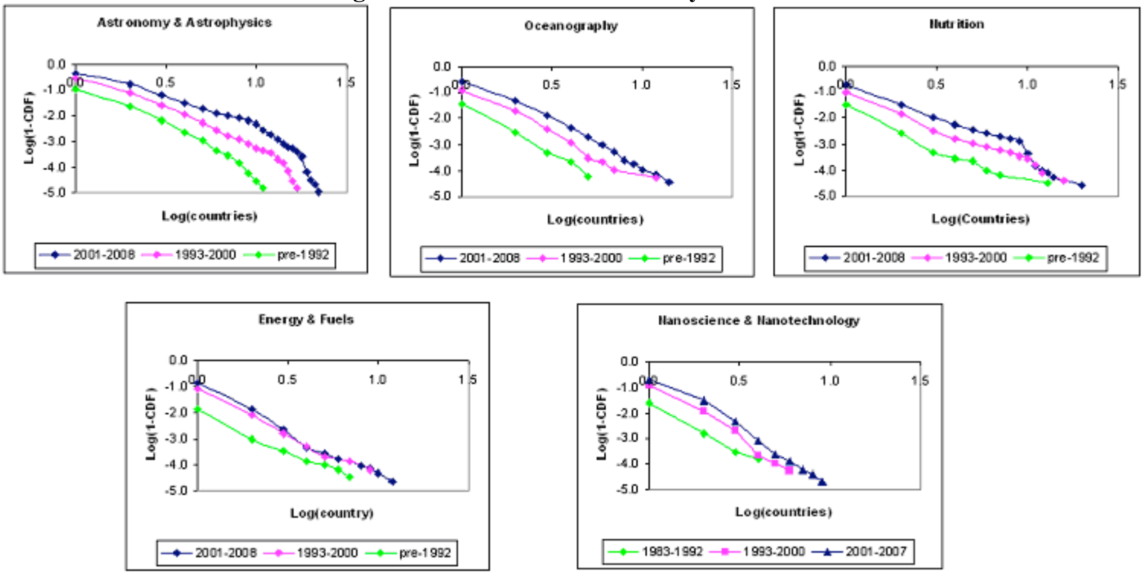
Distribution Analysis

In addition to the mean averages and growth, one can look at the distribution of country collaborations. As previously noted, power laws have a long and varied association with bibliographic data. Due to this association, the distribution of how many countries collaborate on a given publication was tested to see if it fit to a power law. Figure 1 shows the log-log plots of CCDF verse country representation in a given publication for each of the five fields studied with the goodness of fit to a power law in table 4.

Table 16 Power Law Goodness of Fit for Country Collaboration Distribution

Field	Time Period	b + 1	log a	R2	std err	t-stat
Astronomy & Astrophysics	pre-1992	3.728	-0.579	0.967	0.231	-16.14
	1993-2000	3.317	-0.097	0.951	0.195	-17.01
	2001-2008	3.241	0.414	0.865	0.286	-11.34
Energy & Fuels	pre-1992	2.955	-1.987	0.986	0.160	-18.45
	1993-2000	3.344	-1.149	0.986	0.182	-18.4
	2001-2008	3.489	-0.949	0.986	0.138	-25.26
Nanotech & Nanosciences	pre-1992	3.780	-1.631	0.995	0.196	-19.28
	1993-2000	4.503	-0.776	0.982	0.309	-14.56
	2001-2007	4.382	-0.452	0.987	0.188	-23.29
Nutrition	pre-1992	2.777	-1.734	0.957	0.241	-11.52
	1993-2000	2.648	-1.077	0.984	0.102	-25.99
	2001-2008	3.034	-0.460	0.939	0.214	-14.19
Oceanography	pre-1992	3.923	-1.409	0.992	0.199	-19.69
	1993-2000	3.452	-0.853	0.975	0.228	-15.14
	2001-2008	3.525	-0.342	0.990	0.111	-31.83

Figure 9 Distribution of Country Collaborations



The goodness-of-fit is strong for strong for all except the most collaborative of the fields, Astronomy and Astrophysics. A&A has a very strong hook at the end of the 2001-2008 data which starts at 19 countries collaborating. When this hook is removed, OLS regression shows a slope (b+1) of -2.61 with an intercept (log a) of 0.023 and the goodness-of-fit goes up considerably with a R2 of 0.954, standard deviation of 0.143 and t-statistic of -18.21. The hook appears in pre-1992 data starting at when 10 or more countries collaborate and in the 1993-2000 data when 15 more countries collaborate. A similar hook, though not as pronounced, shows in the 2001-2008 graph for nutrition, starting after log 1, or when more than 10 countries collaborate together. A likely explanation of this hook comes from the literature surrounding power-laws seen in social networks. It has been noted by Amaral et al. (2000) and Wagner and Leydesdorff (2005) that the cost of adding additional vertices to a network is a limiting factor, especially in collaborative networks. However, over time the hook begins at a later point suggests that these costs have been decreasing over time at a different rate for each field.

This analysis shows that the scale-free collaboration found by Newman (2001), Jeong et al.(2001), and Barabassi at al.(2002) at the individual scientist level, and scale-free collaboration of scientists collaborating with international scientists found by Wagner and Leydesdorff (2005) also applies at the macro level of countries collaborating together to publish articles. Just like the other studies, the power-law exponent varies by disciplines but falls in a similar range between 2.6 and 3.6, with the exception of nanosciences & nanotechnology (N&N). One of the reasons why N&N's slope is considerably steeper may lay in the fact the N&N is a much "younger" discipline with a smaller select number countries investing heavily in the discipline. This hypothesis will be explored later during the country-level analysis of this chapter.

Core-Periphery Analysis

Degree Distribution

Figure 10 - Distribution of Country's Degree Centrality

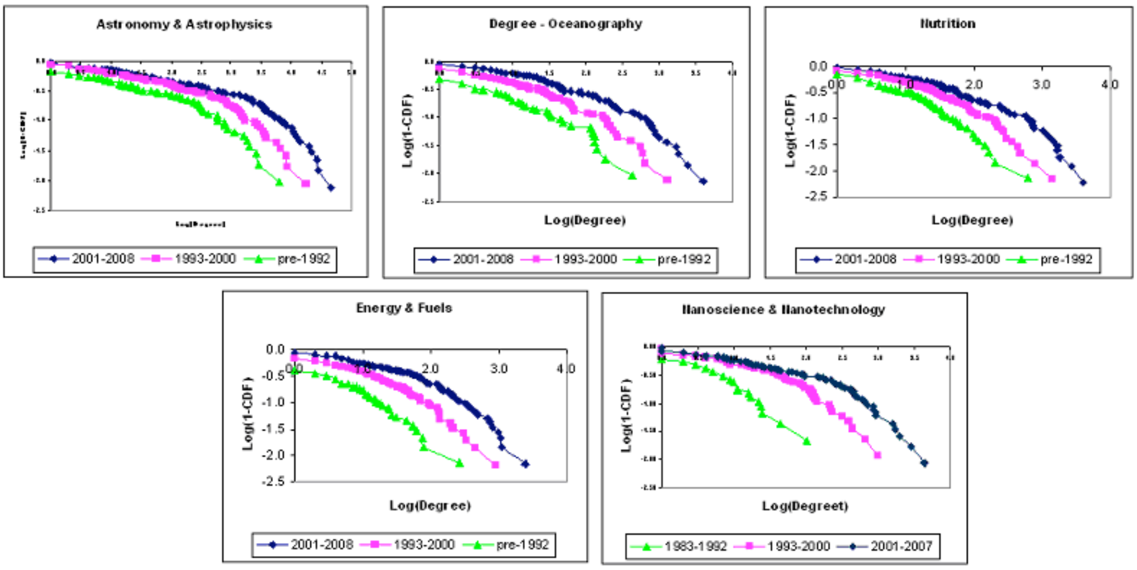
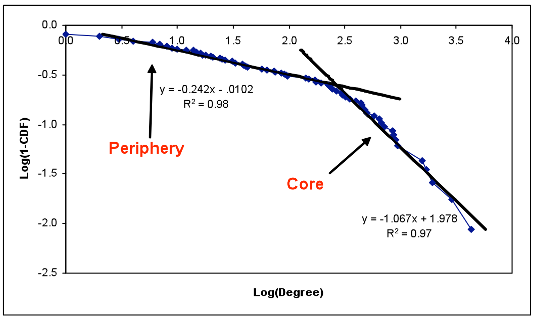


Figure 2 shows the initial graph of the distribution of degree centrality in log-log space. The significant shift to the right over time show that the density of cooperation among countries is growing across all disciplines. The majority of graphs also show a marked discontinuity in which the distribution bends towards a different slope. This bend is characteristic of the core-periphery structure previously discussed and is illustrated in figure 3.

Piece-wise linear regression shows two distinct structures lie within this distribution (see figure 3). An analysis shown in table 6 shows this structure permeating across all disciplines studied.

Figure 11 Nanotechnology and Nanosciences 2001-2007 Degree Centrality Distribution



The cohesiveness of the core varies by field and is measured through a combination of the core (power-law) coefficient, the minimum degree level of core countries, and the core size. The core coefficient is similar to a Gini coefficient seen in economic studies: the closer it comes to 0, the greater the disparity among members. Therefore, the greater the absolute value of the coefficient, the more cohesive the core. The inverse is also true: the greater the minimum degree of the core, the greater the density of cooperation within the core. The analysis in table 6 shows three distinct core-periphery patterns among the fields.

The first pattern is a highly dense and interconnected core and a largely disperse from the periphery as seen in Astronomy & Astrophysics. Over time, as the size of the core has grown so too has its density as reflected by the high minimum degree level seen in each time period. Additionally, the disparity between the core and periphery coefficients is suggestive that it is increasingly difficult for countries to travel from the periphery to the core in this discipline in the future.

The second pattern features a large but highly disconnected core membership. This is seen in the disciplinary fields of energy and nano, which are mostly loosely related to technological fields. This pattern suggests that countries are working largely independently of each other, more so in energy and fuel research than in nanotechnology.

The third pattern falls in between the first two and features a much smaller core of countries than the other disciplines but one that is highly dense and is reflected in oceanography and nutrition. This pattern has high core coefficients and a minimum degree ranging twice that seen in the second patter that suggests a high level of interconnectedness and more equity in the distribution of cooperation amongst core members.

Table 17 Degree Core Coefficients

	Astronomy			Nanotechnology			Energy			Nutrition			Oceanography		
	-'92	93'-00	01-'08	-'92	93'-00	01-'08	-'92	93'-00	01-'08	-'92	93'-00	01-'08	-'92	93'-00	01-'08
Core Coef.	-0.87	-1.01	-1.03	-0.94	-1.11	-1.07	-1.02	-1.15	-1.16	-1.10	-1.30	-1.42	-1.38	-1.23	-1.29
R-Sq	0.97	0.97	0.96	0.94	0.98	0.97	0.95	0.98	0.97	0.94	0.99	0.97	0.85	0.97	0.98
std error	0.03	0.04	0.04	0.13	0.04	0.03	0.08	0.04	0.05	0.11	0.04	0.06	0.26	0.06	0.04
t-stat	-25.68	-22.79	-24.53	-7.11	-31.05	-31.12	-12.96	-29.12	-24.72	-9.81	-33.92	-21.89	-5.42	-20.38	-30.46
Per. Coef.	-0.21	-0.23	-0.19	-0.57	-0.29	-0.24	-0.55	-0.44	-0.33	-0.56	-0.45	-0.39	-0.48	-0.42	-0.36
R-Sq	0.99	0.97	0.99	0.91	0.93	0.98	0.93	0.95	0.94	0.92	0.93	0.96	0.97	0.94	0.95
std error	0.00	0.01	0.00	0.06	0.02	0.01	0.04	0.02	0.01	0.03	0.02	0.01	0.02	0.02	0.01
t-stat	-48.78	-41.10	-71.52	-9.64	-18.01	-42.43	-14.25	-26.56	-26.84	-19.24	-24.56	-37.74	-23.82	-23.80	-32.41
Min. Degree	595	1147	2937	16	83	225	24	68	185	79	153	558	117	170	425
Core Size	13	20	26	7	19	29	10	19	23	9	15	18	7	14	17
Core Share	84.3%	89.2%	91.7%	82.1%	87.8%	94.7%	76.1%	78.7%	82.0%	75.0%	79.9%	76.1%	72.2%	80.2%	81.4%

Table 18 - Article Core Coefficients

	Astronomy			Nanotechnology			Energy			Nutrition			Oceanography		
	-'92	93'-00	01-'08	-'92[37]	93'-00	01-'08	-'92	93'-00	01-'08	-'92	93'-00	01-'08	-'92	93'-00	01-'08
Core Coef.	-0.86	-0.88	-0.87	n/a	-0.86	-0.95	-0.81	-1.05	-1.20	-0.75	-0.99	-1.09	-0.76	-0.98	-1.15
R-Sq	0.95	0.97	0.97	n/a	0.99	0.98	0.94	0.94	0.95	0.95	0.95	0.95	0.95	0.96	0.95
std error	0.06	0.04	0.03	n/a	0.02	0.03	0.07	0.08	0.07	0.06	0.07	0.05	0.04	0.05	0.07
t-stat	-13.31	-22.88	-29.91	n/a	-44.06	-33.15	-11.37	-12.80	-17.67	-13.59	-14.50	-20.24	-16.92	-19.06	-16.58
Per. Coef.	-0.27	-0.24	-0.21	n/a	-0.24	-0.25	-0.41	-0.39	-0.32	-0.38	-0.39	-0.32	-0.37	-0.35	-0.32
R-Sq	0.95	0.97	0.99	n/a	0.94	0.97	0.89	0.94	0.94	0.95	0.95	0.96	0.97	0.98	0.98
std error	0.01	0.01	0.00	n/a	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
t-stat	-29.98	-41.69	-68.93	n/a	-22.95	-36.60	-21.57	-30.66	-32.92	-32.09	-34.72	-40.49	-32.47	-41.65	-50.87
Min. Article	505	859	1040	n/a	173	601	579	550	700	584	613	511	169	274	607
Core Size	12	20	29	n/a	22	21	10	13	19	11	12	23	16	17	18
Core Share	85.4%	89.3%	94.1%	n/a	91.7%	89.8%	83.0%	73.8%	80.6%	83.5%	77.3%	85.5%	92.40%	87.60%	84%

[37] There was no significant core-periphery structure during this time period.

Article Distribution

Figure 12- Distribution of Country's Article Output

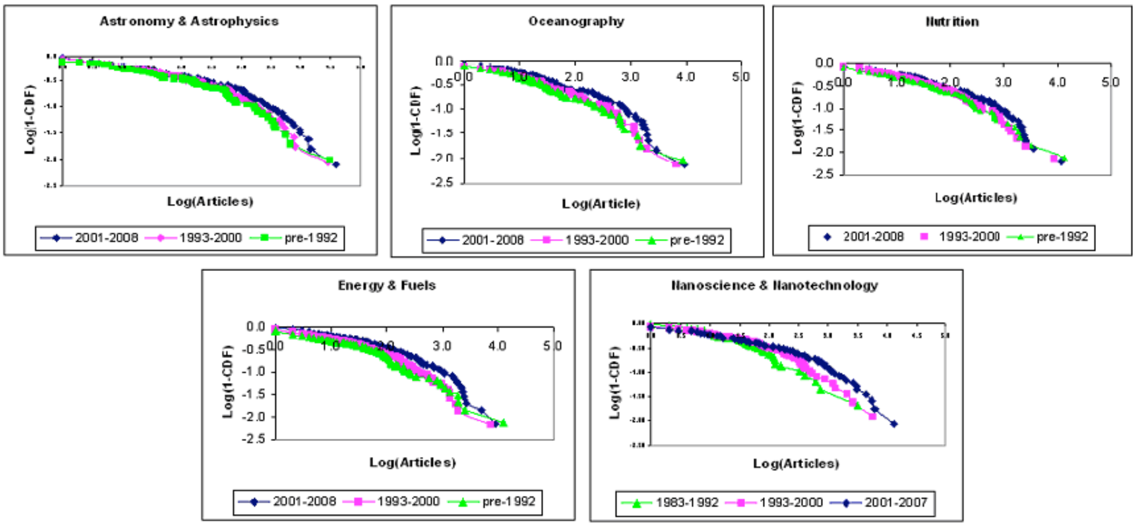


Figure 4 shows the initial graph of the distribution of a country's article output in log-log space. The article output is the number of articles published in which at least one author was from a given country. Just as in the degree distribution, there is a strong 2-tier structure evident in the graph. However, in contrast to degree distribution seen in figure 2, there is not as pronounced growth (symbolized by a right shift in the graph) in overall article output. The analysis of the two-tiered structure is shown in table 7.

The power law exponent is significantly lower in both the article count's core and periphery structures than in the degree distribution. Thus, while overall output continues to grow and the core gets wider, the inequality of output between countries has decreased at a rate much slower than inequality of cooperation signifying that countries are depending more on cooperation for growth rather just outputting new articles.

In astronomy, while the core has grown over time, there has been little change in the core coefficient. A possible interpretation of this would be that the structure has reached some type of equilibrium. A possible explanation is that only astronomy has reached this equilibrium state would be that it has long had the highest amount of international cooperation and has reached some type of plateau.

In contrast, nanotechnology, the youngest of all the disciplines studied, went from having no discernable core-periphery structure in the first time period (the distribution fit closer to a single power law structure rather than a two-tier structure) to a large core in the second time period that then stabilized in the third time period with output become more equal in the core.

Energy and nutrition saw little growth in the minimum amount of articles published to enter the core while having a large increase in the core coefficient. A quick glance of the graph in figure 4 for these disciplines show a distinct break in the distribution illustrates this behavior. One possible explanation could be that investment in core countries for these disciplines has stabilized.

Oceanography shows a similar break in the figure 4 but in this case there is significant increase in the minimum articles but little growth in the size of the core. This may be the case that countries interested in oceanography have increased their investments whereas other countries choose not to pursue investments, quite possibly due to the geographic nature of this discipline. Indeed, landlocked countries in Europe, notably Austria and Switzerland, which are part of the core in may other disciplines are not part of the core of oceanography.

Core-Periphery Membership

The core-periphery structure seen in the degree and article distributions has significant membership overlap though the rank order varies considerably[38]. The majority of the differences of country membership occur with countries near the edge of the core-periphery structure. A good example of this can be seen in nutrition. In this field, India is publishing enough articles to be in the core of the article distribution but has very low degree centrality due to the fact that it has little international coauthorship (<7% prior to 2000 and 16% from 2001-2008). Switzerland on the other hand has the opposite pattern; it has a very low number of articles and doesn't enter the core in article counts prior to 2001 but has the highest level of internationally coauthored publications of any European country in all three time periods thus putting it squarely in the core in the degree centrality rankings. In India's case, you have a country working heavily in the area of nutrition science without accessing the global talent pool thus keeping them in the periphery. Whereas in Switzerland you have a country that is dependent on working with the core countries while not having enough of its own production to reach the critical threshold until the 2001-2008 time period. Thus it is for this reason that for a country to considered a core country within a discipline it must exist in both the degree and article cores. The result of this analysis is shown in table 7.

[38] The rank order of countries in the core can be seen in the appendix

Table 19 Number of disciplines in which the country has core membership

Canada	*5*	*5*	*5*
France	5	5	5
Germany	5	5	5
United Kingdom	5	5	5
USA	5	5	5
Japan	5	5	5
Italy	4	5	5
Spain	1	5	5
Australia	3	4	5
Netherlands	2	4	5
Sweden	1	4	5
China	0	3	5
Russia	1	4	4
India	1	2	3
Switzerland	0	2	3
Denmark	1	1	3
Belgium	0	1	3
Brazil	0	1	3
South Korea	0	1	3
Poland	0	2	2
Norway	1	1	2
Greece	0	0	2
Finland	0	0	2
Taiwan	0	0	2
Austria	0	2	1
Mexico	0	1	1
Chile	0	1	1
Singapore	0	0	1
New Zealand	0	0	1
Turkey	0	0	1
Czech Republic	0	1	0
South Africa	1	0	0

The membership in the cores is similar to pattern observed by Glänzel (2001, 2008). The EU-US-Japan triad has dominated the core historically, with some exceptions. After the fall the USSR, Russia joined the core of the scientific community in all disciplines except nutrition. With the exception of New Zealand and Chile, most the other countries that have limited membership to the cores enter through investments in energy & fuels and nanotechnology, while those with membership in 3 cores also include astronomy and astrophysics. New Zealand's and Chile's core membership can be attributed primarily to geography as New Zealand is an island nation and Chile has many countries putting their southern observatories in the arid Atacama Desert. This research also confirms observation by Glänzel et al (2008) that China is integrating in the core of all sciences, though its membership in the non-technology focus disciplines of nutrition and oceanography is at the edge of the core.

Citation Impact Analysis

Various bibliometrics studies have reported the benefits of international scientific collaboration for specific fields tend to have higher citation rates than those with authors from a single country (Moed 2005). Glänzel and Schubert (2004) reviewed these studies and were cautious about generalizing their outcomes an interpreting their results. Moed (2005) further analyzed bi-lateral international scientific cooperation to test if the mean citation rate of bi-lateral international collaborations (BIC) was great than the mean citation rate of non-international collaborations (NIC) for the top 20 producers of domestic articles. This analysis seeks to extend his work in several important ways:

- Looking at citation impact and distribution of BIC based on a core-periphery model
- Assessing the citation impact from both core and periphery country's point of view regardless of sequence of authors listed
- Longitudinal Analysis is done over three distinct time periods
- As stated in the data section, multi-lateral international collaborations (MIC) were broken down into multiple BIC. In Moed's original analysis, MICs were excluded.

The citation impact in the three fields in table 9 shows qualitative similarities to Moed's analysis. The citation impact of BIC is greatest when two core countries are collaborating, which also makes up the bulk of collaborations that are taking place. As the share of the collaborations became more between core countries over time, the citation impact of these collaborations also grew. The increased citation impact in these collaborations show the frontier of science is increasingly being pushed through international collaborations. Conversely, collaboration between the core-periphery as a percentage of BIC shrank during this same period. The citation impact to core countries (denoted in the row core-peri) also shrank during this time while the impact to periphery countries (row peri-core) grew. Correspondingly, the collaborations among periphery countries shrank and the scientific impact is considerably less than when the periphery contributes with the core.

Thus there is an incentive that if one wants to maximize the citation impact of their research; one need collaborate with a scientist from a core country that is not from the same country. Additionally, one possible explanation of the low citation impact in core-periphery BIC is that collaboration between scientifically advanced countries to developing countries are more about the transfer of knowledge rather than the creation of knowledge, at least within these fields of science.

Table 20 - Citation Impact of international collaborations on Astronomy, Nutrition and Oceanography

	Astronomy & Astrophysics								
	pre-1992			**1993-200**			**2001-2008**		
	% of BIC	BIC<NIC	BIC>NIC	% of BIC	BIC<NIC	BIC>NIC	% of BIC	BIC<NIC	BIC>NIC
All	13802	34.5%	65.5%	45234	24.6%	75.4%	152838	24.3%	75.7%
Core-Core	61.9%	6.4%	93.6%	72.7%	8.2%	91.8%	80.2%	4.7%	95.3%
Core-Peri	25.1%	50.3%	49.7%	24.8%	42.1%	57.9%	18.3%	43.4%	56.6%
Peri-Core		20.1%	79.9%		11.9%	88.1%		11.2%	88.8%
Peri-Peri	12.9%	40.1%	59.9%	2.5%	27.7%	72.3%	1.5%	31.0%	69.0%

	Nutrition								
	pre-1992			**1993-200**			**2001-2008**		
	% of BIC	BIC<NIC	BIC>NIC	% of BIC	BIC<NIC	BIC>NIC	% of BIC	BIC<NIC	BIC>NIC
All	1378	42.3%	57.7%	4129	29.2%	70.8%	15122	37.7%	62.3%
Core-Core	25.5%	27.8%	72.2%	32.2%	17.0%	83.0%	59.0%	8.9%	91.1%
Core-Peri	60.2%	59.8%	40.2%	53.9%	49.7%	50.3%	35.3%	60.9%	39.1%
Peri-Core		32.7%	67.3%		24.5%	75.5%		21.2%	78.8%
Peri-Peri	14.4%	38.3%	61.7%	13.9%	20.3%	79.7%	5.7%	40.7%	59.3%

Oceanography									
	pre-1992			1993-200			2001-2008		
	% of BIC	BIC<NIC	BIC>NIC	% of BIC	BIC<NIC	BIC>NIC	% of BIC	BIC<NIC	BIC>NIC
All	656	39.1%	60.9%	3592	34.9%	65.1%	12425	36.1%	63.9%
Core-Core	47.9%	23.3%	76.7%	55.5%	29.5%	70.5%	58.4%	18.3%	81.7%
Core-Peri	45.4%	44.6%	55.4%	39.4%	49.4%	50.6%	36.4%	49.6%	50.4%
Peri-Core		32.4%	67.6%		25.7%	74.3%		24.6%	75.4%
Peri-Peri	6.7%	50.0%	50.0%	5.1%	30.4%	69.6%	5.2%	40.4%	59.6%

In contrast to the findings in table 9, the more technology oriented fields of energy and nanotechnology, shown in table 10, show a substantially different collaborative behavior. In these disciplines, the substantial increase in core-core BIC has not seen a corresponding increase in citation impact. This means that for these fields, there is no expectation of greater citation impact for BIC, thus no incentive for scientists to seek international partners. In fact, there is a strong disincentive in terms of citation impact for a scientist from the core to collaborate with those in the periphery as the citation impact is significantly less than a NIC. The pattern seen in the degree distribution (see table 6) seems to indicate that the work at the frontier is performed equally at the national level as well as at the international level. Thus there must be a substantial difference in the driving force behind international collaboration for the two disciplines shown in table 9 than in the three disciplines shown in table 8.

Table 21 - Citation Impact of internationally co-authored papers on Energy and Nano

Energy & Fuels									
	pre-1992			1993-200			2001-2008		
	% of BIC	BIC<NIC	BIC>NIC	% of BIC	BIC<NIC	BIC>NIC	% of BIC	BIC<NIC	BIC>NIC
All	523	44.3%	55.7%	2511	53.7%	46.3%	7977	58.4%	41.6%
Core-Core	34.2%	37.1%	62.9%	37.7%	36.3%	63.7%	51.5%	45.4%	54.6%
Core-Peri	55.8%	52.3%	47.7%	49.6%	60.1%	39.9%	41.3%	70.0%	30.0%
Peri-Core		35.1%	64.9%		47.1%	52.9%		52.9%	47.1%
Peri-Peri	9.9%	51.1%	48.9%	12.7%	59.7%	40.3%	7.2%	57.6%	42.4%

Nanosciences & Nanotechnology									
	pre-1992			1993-200			2001-2008		
	% of BIC	BIC<NIC	BIC>NIC	% of BIC	BIC<NIC	BIC>NIC	% of BIC	BIC<NIC	BIC>NIC
All	189	47.6%	52.4%	2802	60.7%	39.3%	13688	60.3%	39.7%
Core-Core	43.4%	40.6%	59.4%	70.4%	60.3%	39.7%	70.4%	52.7%	47.3%
Core-Peri	46.6%	60.8%	39.2%	27.2%	69.5%	30.5%	26.3%	66.3%	33.7%
Peri-Core		33.3%	66.7%		52.7%	47.3%		59.9%	40.1%
Peri-Peri	10.1%	55.6%	44.4%	2.4%	59.8%	40.2%	3.3%	59.8%	40.2%

Conclusion

In summary, even though there is a distinct and quantifiable core-periphery structure evident that varies across fields of science. The countries that tend to compose the majority of the core are similar with variations around the edges of the core. Originally comprised of a handful of countries in the core of any field of science, the core has grown to include 29 countries that maintain membership in at least one core. There are several implications to this phenomenon. For non-technology intensive fields, membership in the core increases the attractiveness of a country's scientific base. However, those countries left in the periphery are becoming increasingly isolated from the scientific elite. This isolation is growing as the gap widens in their relative decline in article output, degree centrality and citation impact. To understand how to overcome this isolation, a more detailed analysis of the collaborative behavior at the bilateral level needs to be conducted.

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