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Prominent institutions in international collaboration network in astronomy and astrophysics

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Abstract The study explores the international collaboration network consisting of 606 astronomical institutions through the analysis of international coauthored papers published in six journals in astronomy and astrophysics from 2001 to 2009. It shows that the Istituto Nazionale di Astrofisica (INAF) and European Southern Observatory (ESO) are the most notable actors, with the highest values of centrality in the network, while Japan Meteorological Agency (JMA) is the only institution that is completely separated from others. It is observed that national academies in major countries, international organizations, and large observatories are more likely to be the central actors. Yet some world-famous astronomical institutions, such as CfA, NASA, and Caltech, are identified as remarkable actors in the network, they show no strikingly high scores in the centrality measures. Overall, astronomical institutions' network position varies with time; nevertheless, not all of institutions present considerable changes during the investigation periods. While some institutions moved from central to relative peripheral positions, or in the opposite direction, the institutions which are positioned at the very center of the network tend to be stable over time.

Keywords Astronomy and astrophysics · Scientific collaboration · International collaboration · Co-authorship network · Network centrality

Introduction

International collaboration has prevailed in science. An extensive body of research has indicated that a growing number of papers are written jointly by authors from different

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countries (e.g. Georghiou 1998; Glänzel 2001a, b; Luukkonen et al. 1992, 1993; Miquel and Okubo 1994; Suárez-Balseiro et al. 2006; Wagner and Leydesdorff 2005). Regardless of geographical, political, cultural, and other boundaries, many scientists, organizations, governments, and various research units are inclined to establish cross-national scientific connections. Such coalition serves as a vital means to enrich scientific discoveries around the world. Scientists can be benefited from intellectual exchanges with foreign colleagues and reduce costs by sharing resources and apparatus in other countries. For R&D administrators' perspectives, international collaboration is encouraged both concerning scientific research as well as its association to high visibility in scientific community (Barjak and Robinson 2007; Bordons et al. 1996). The positive relationship between international collaboration and citation impact has been shown in many studies (Arunachalam et al. 1994; Glänzel 2000, 2001a, b; Glänzel and de Lange 2002; Glänzel and Schubert 2001; Narin et al. 1991; van Raan 1998). It is found that more countries a paper is assigned, the higher citation rate there will be of it (Aksnes 2003; Ruane and Tol 2008; Yoon and Young 2008). Both developing countries and wealthier nations may benefit from international collaboration (Glänzel et al. 1999).

International collaboration is important not only because it is prevalent in and around the scientific community, but also because it can be used for illustrating the worldwide science network. Collaborative work is often viewed as evidence of scientific connections between and among research units, and thus draws the attention of network analysts. Facilitated by the ease of long-distance travel and advances in communication technology, cross-national scientific connection has received even more attention in recent decades. There is a highly interconnected network in science globally (Wagner and Leydesdorff 2005, 2008).

Obviously the overall collaboration network is expanding as more and more countries plunge into international collaborative research (Glänzel 2001a, b; Lorigo and Pellacini 2007; Wagner and Leydesdorff 2005; Leydesdorff and Wagner 2008). Nevertheless, the scales largely differ by fields. It is observed that disciplines requiring specific resources, such as geology and oceanography, and expensive facilities, such as astronomy and astrophysics and particle physics, have a tendency to produce more multinational co-authored publications (Luukkonen et al. 1992; Velho 1995).

Astronomy and astrophysics is a highly internationalized field (Adams et al. 2005). There are many international cooperative projects and papers produced in this field (Abt 1981, 1990; White 1992). It particularly manifests a high rate of international collaboration in comparison with many other scientific fields (Abt 2007; Beaver and Rosen 1978; Luukkonen et al. 1992; Russell and Almada de Ascencio 1997). Abt (2007) estimated that over half of astronomical papers are jointly published by multiple countries. He found that about a half of astronomical papers are written internationally, while only 10 % of papers are published by single authors. The proportion of multinational papers in astronomy is the highest among 16 investigated scientific fields. In the exploration of the top 110 U.S. universities, Adams' team (Adams et al. 2005) also pointed out that astronomy, mathematics and statistics, and physics are the three most internationalized fields. According to van Raan (1998), about 60 % of Dutch astronomical articles are the results of collaboration between the Netherlands and other countries. Regarding the international co-authorship network, Wagner (2005) identified astronomy as a highly internationally networked discipline by the growing number of countries that are linked up in astronomical research.

Longitudinal analyses showed that the volume of multinational astronomical co-authorship has increased constantly in astronomical literature since the 1970's (Abt 1990; Hearnshaw 2007). The number of international co-authored publications and astronomy-

related organizations has grown over the past decades (Heck 2000). Many reasons can be accounted for the trend toward internationalization in astronomy and astrophysics, including advanced communication technology facilitating long-distance collaboration, international conferences that bring together astronomers from different countries, journal policies that encourage astronomical research in developing countries, professional equipment that is set up abroad, and research data that are collected globally (Abt 2000).

Despite these findings, the configuration of the international collaboration network in astronomy and astrophysics remains unclear. Little attention has been given to which groups of actors are placed in the center and the periphery of the network, and how this varies with time, for instance. In order to address such network characteristics of the astronomical community, this study uses the network analysis method to identify the prominent actors in the international collaboration network.

Conceptually, the collaboration network consists of a set of nodes and relational ties. The nodes often denote research units (e.g. scientists, institutions, and countries), and the relational ties are the collaborative relations, which can be measured by either the existence or the strength of collaborative relationships. Many relevant studies have analyzed international collaboration networks at country level, yet the same methodologies are appropriately applied to studies at institutional level, as institutions are the main driver for scientific research. In order to contribute to our understanding of scholarly communication in the astronomical community, the study explores international collaboration network among research institutions in astronomy and astrophysics. There is an attempt to investigate which of the institutions are positioned in the very central and peripheral positions in the international co-authorship network; moreover, the study shows how the group of prominent institutions changed over the investigated time periods.

Methodology

The study explores the international collaboration network, consisting of 606 astronomical institutions. It compiled 57,934 papers in the six astronomical journals of *Astronomical Journal* (AJ), *Astronomy & Astrophysics* (A&A), *Astronomy and Astrophysics Review* (A&ARv), *Astrophysical Journal* (ApJ), *Astrophysical Journal Supplement Series* (ApJS), and *Monthly Notices of the Royal Astronomical Society* (MNRAS) from 2001 to 2009. All the analyzed institutions need to publish at least ten papers in the six selected journals during the period and are indexed by StarGuides Plus, a directory of worldwide astronomical organizations. The sample of this study consists of 606 astronomical institutions worldwide, including eight international organizations.[1] A majority of these institutions are universities and academic institutes. While functioning as observing facilities, large and international observatories are regarded as astronomical institutions in this study because they also focus on astronomical research and operate like independent organizations. This study compiles bibliographic records from SAO/NASA ADS and unifies the variations of institution names in the dataset.

[1] There are eight astronomical institutions, including the Center for Backyard Astrophysics, European Southern Observatory (ESO), European Space Agency (ESA), Gemini Observatory, the International Center for Astronomical, Medical and Ecological Research (ICAMER), the Institut de Radioastronomie Millimétrique (IRAM), National Optical Astronomy Observatory (NOAO), and Vatican Observatory classified as international organizations in the study. These institutions are presented at the highest level of organization in the analysis.

Table 1 Distributions of productivity for 606 astronomical institutions

Intervals	2001–2003		2004–2006		2007–2009		2001–2009	
	N	%	*N*	%	*N*	%	*N*	%
≤99	481	79.37	457	75.41	419	69.14	284	46.86
100–199	66	10.89	73	12.05	98	16.17	94	15.51
200–299	23	3.80	31	5.12	28	4.62	79	13.04
300–399	18	2.97	16	2.64	24	3.96	39	6.44
400–499	2	.33	11	1.82	13	2.15	20	3.30
500–599	8	1.32	4	.66	6	.99	13	2.15
600–699	1	.17	4	.66	3	.50	11	1.82
700–799	2	.33	3	.50	6	.99	10	1.65
800–899	1	.17	2	.33	1	.17	11	1.82
900–999	0	.00	0	.00	3	.50	7	1.16
≥1,000	4	.66	5	.83	5	.83	38	6.27
Statistics								
N	606		606		606		606	
Mean	79.24		95.60		115.06		289.9	
SD	149.15		175.61		206.59		527.15	
Min.	0		0		0		10	
Max.	1,612		1,900		2,320		5,832	

To explore the dynamics of the international collaboration network in astronomy and astrophysics, this study slices the whole span of time into shorter periods of three-year windows of 2001–2003, 2004–2005, and 2007–2009. Table 1 shows the distributions of productivity for the 606 astronomical institutions across the three periods. It indicates that the distribution of productivity is highly skewed for each period of 2001–2003, 2004–2005, and 2007–2009, yet a slight decrease in skewness is observed over time. A large proportion of institutions produced less than 100 papers in the six selected journals (79.37 % in 2001–2003, 75.41 % in 2004–2006, and 69.14 % in 2007–2009), while the average is around 80–120 papers (79 papers in 2001–2003, 96 papers in 2004–2006, and 115 papers in 2007–2009).

This study uses co-authorship analysis to measure international collaborations among the 606 astronomical institutions. The occurrence of international collaboration is indicated by a co-authored paper which presents institutions in multiple countries. Single author papers are not included in the analysis, even though there is more than one country shown in author address fields. Like most collaboration studies, the current research employs the total counting method in co-authorship analysis. Every coauthor equally receives one count, no matter which order of authorship it presents in a collaborative article and how many countries were presented in the paper. Despite its limitation of not distinguishing between papers with authors from two countries from ones that have three or more countries present, it is observed that total counting has been widely used in many studies of research collaborations. Researchers could take the number of countries into account in future studies of international collaborations.

In terms of network analysis, we use the concept of network centrality to measure the importance of astronomical institutions in the international collaboration network. It is assumed that nodes at the center of the network can be regarded as the most important

actors in the analyzed activity. Centrality measures are therefore widely applied for evaluating actors' prominence within a complete network. To give a comprehensive idea of prominent actors, this study takes degree centrality, closeness centrality, and betweenness centrality indices into consideration. Institutions with a high level of centrality, measured by any of the indices, are viewed as central, prominent actors in international collaboration network. The indicators are defined as follows:

Degree centrality is the most intuitive and prominent indicator in network analysis. It is measured by the number of ties that a node has in the network, and therefore can indicate the popularity of actor among a group. In this study, an actor with high value of degree centrality is indicated as an institution which has conducted research collaborations with diverse foreign institutions, thus it is viewed as a popular collaborator in the international realm.

$$C_D(n_i) = \sum_{j=1}^{g} X_{ij},\ i \neq j \tag{1}$$

where X_{ij} is the number of ties between node i and j.

Normalized:

$$C_D\prime(n_i) = \frac{C_D(n_i)}{g-1} \tag{2}$$

where g is the total number of nodes in the network.

Closeness centrality is often used for showing the ability to access information through network members. It indicates the degree a node is near all other nodes in network by calculating as the inverse of the sum of the geodesic distance of each node to every other node in the network. In this study, an institution with high value of closeness centrality is viewed as an actor which is relatively close to all others in the international collaboration network.

$$C_C(n_i) = \frac{1}{\sum_{j=1}^{g} d(n_i, n_j)},\ i \neq j, \tag{3}$$

where $d(n_i, n_j)$ is the number of geodesic distance between node i and j.

Normalized:

$$C_C\prime(n_i) = C_C(n_i)(g-1) \tag{4}$$

Betweenness centrality is identified as a powerful indicator for actors that lie on the paths connecting to others. It is used to measure the extent to which a node lies between other node pairs in the network. Actors with higher betweenness centrality have greater power in the sense that they serve as brokers and can control the flow of information through the network. In this study, an institution with higher value of betweenness centrality is more likely to play an important intermediary role that bridges clusters in the international collaboration network.

$$C_B(n_i) = \sum_{j<k} \frac{g_{jk}(n_i)}{g_{jk}},\ i \neq j \neq k \tag{5}$$

where $g_{jk}(n_i)$ is the number of geodesic distance between node j and k that contain node i, g_{jk} is the number of geodesic distance between node j and k.

Table 2 Statistics of centrality in the network, 2001–2009

Statistics	No. of papers		Degree centrality		Closeness centrality		Betweenness centrality	
	Total	Intl.	w/o Nrm.	Normalized	w/o Nrm.	Normalized	w/o Nrm.	Normalized
Mean	289.90	222.80	98.15	16.23	.0005760	34.82	266.12	.15
SD	527.15	405.67	86.95	14.37	4.00551E−05	2.81	686.22	.38
Min.	10.00	10.00	.00	.00	.0000000	.00	.00	.00
Max.	5832.00	4735.00	480.00	79.34	.0007496	45.35	10318.14	5.65

Normalized:

$$C_B\prime(n_i) = \frac{C_B(n_i)}{(g-1)(g-2)/2} = \frac{C_B(n_i) \times 2}{(g-1)(g-2)} \quad (6)$$

The above measures of centrality are widely used in network analysis. This study comprehensively uses all of the three indicators to define the core and peripheral actors in international collaboration network. The statistics of the centrality measures are shown in Table 2.

Result

On average an institution connects with 98 foreign counterparts in the network. Yet the variance of the measure is high (*Mean nodal degree* = 98.15, *SD* = 86.95). Table 3 shows that over one-third of institutions (38.45 %) have connected to less than fifty external partners. Relatively a smaller number of institutions have held over hundreds of cross-national linkages in the network.

As for the time-varying characteristics, an institution averagely has links with 43 (*Mean* = 42.73, *SD* = 49.76) counterparts in 2001–2003 within the international collaboration network, and the number keeps rising to 53 (*Mean* = 52.96, *SD* = 57.58) in 2004–2006 and 66 (*Mean* = 66.05, *SD* = 76.18) in 2007–2009. The one-way analysis of variance (ANOVA) test yields *F* values of 42.91 and 24.07, indicating significant

Table 3 The number of collaborating foreign institutions, 2001–2009

Number of collaborating foreign institutions (within the network)	Number of institutions (%)	Accumulative number of institutions (%)
≤49	233 (38.45 %)	233 (38.45 %)
50–99	134 (22.11 %)	367 (60.56 %)
100–149	88 (14.52 %)	455 (75.08 %)
150–199	69 (11.39 %)	524 (86.47 %)
200–249	39 (6.44 %)	563 (92.90 %)
250–299	24 (3.96 %)	587 (96.86 %)
300–349	14 (2.31 %)	601 (99.17 %)
350–399	3 (.50 %)	604 (99.67 %)
≥400	2 (.33 %)	606 (100.00 %)

$N = 606$

differences ($p < .001$) among the means of the three periods in the terms of collaborating foreign institutions. The means of the periods are statistically different from one another according to Tukey's post hoc test at the confidence level of 1 %.

In terms of the network structure, network density measures exhibit a loosely coupled network structure in this study. The international collaboration network that consists of 606 nodes and 29,736 active links, and being divided by 313,356 maximum possible cross-national ties, results in a density of .19. It means that only 19 % of the total number of possible ties really present in the network. This density implies that institutions in the network in general do not extensively contact with each other. The apparent growth of cross-national links among astronomical institutions results in an increasing density of the network. The total network density is .08 in 2001–2003 and slightly rises to .10 in 2004–2006 and .13 in 2007–2009. The increase indicates that the institutions of the network are becoming more integrated and dependent on one another in international collaborations. Even though there is no extreme change in the values, the dynamic structure of the international collaboration network in astronomy and astrophysics is still evident. Another indicator, degree centralization, shows a consistent result with density. The moderately high degree centralization of 63.33 % shows that cross-national relationships within the network are to a less extent dominated by a few central members. Some institutions are clearly more active than others in international collaboration, but it is not observed that a nucleus keeps ties with a set of otherwise isolated actors. The indicator starts from 50.63 % in 2001–2003, reaches 54.57 % between 2004 and 2006, and keeps rising to 57.37 % in 2007–2009, indicating that relational ties tend to be concentrated on a small number of actors in the network. These facts can be interpreted as a more compact, dense and centralized network emerged in the later periods. More international connections have been built over time in astronomical collaboration network.

Central and peripheral institutions in the international collaboration network

Overall, closeness is highly correlated with degree centrality. Institutions which have coauthored with more foreign organizations have better accessibility to the others in the network. Additionally, institutions show rather high or moderate values of these two measures but have very low scores of betweenness centrality. No single institution plays a dominant role in connecting pairs of other foreign institutions in the network. Zooming in on the top ten central institutions in Table 4, it appears that the Istituto Nazionale di Astrofisica (INAF) in Italy and the European Southern Observatory (ESO) are the most notable actors, with the highest values on the three measures of centrality. They both have direct connections with many foreign partners and are close to all the other network members, with similarly high levels of degree and closeness centrality. INAF holds 79.34 and 45.35 in degree and closeness centrality, respectively, and the values are 72.23 and 43.94 for ESO. In terms of betweenness centrality, INAF (with a score of 5.65) has much more power than ESO (with a score of 2.66) on controlling the interactions between two nonadjacent institutions. INAF is definitely more likely to be an intermediary in the network, in spite of the small value of its betweenness centrality.

Other visible actors, following INAF and ESO, include the Russian Academy of Sciences, the Observatoire de Paris-Meudon, the National Optical Astronomy Observatory (NOAO), the Chinese Academy of Sciences, and the University of Cambridge. They are all popular partners in the global astronomical community and have short connection paths to various foreign institutions. It seems that national academies of major countries, international organizations, and large observatories are more likely to occupy the center of the international collaboration network in astronomy and astrophysics.

Table 4 Institutions with highest centrality in the network, 2001–2009

Institution	Country	No of papers	Normalized centrality measure (rank)		
			Degree	Closeness	Betweenness
Istituto Nazionale di Astrofisica	Italy	5,832	79.34 (1)	45.35 (1)	5.65 (1)
European Southern Observatory	International	3,105	72.23 (2)	43.94 (2)	2.66 (2)
Russian Academy of Sciences	Russia	2,338	61.98 (3)	42.04 (3)	2.35 (3)
Observatoire de Paris-Meudon	France	1,508	61.98 (3)	42.04 (3)	2.27 (4)
National Optical Astronomy Observatory	International	1,951	60.00 (5)	41.70 (5)	1.94 (5)
Chinese Academy of Sciences	China	1,738	56.69 (6)	41.13 (6)	1.49 (6)
University of Cambridge	UK	2,468	56.53 (7)	41.05 (7)	1.38 (8)
European Space Agency	International	1,073	55.87 (8)	40.96 (8)	1.10 (16)
Consejo Superior de Investigaciones Científicas	Spain	1,222	55.21 (9)	40.88 (9)	1.00 (18)
Instituto de Astrofísica de Canarias	Spain	1,446	54.55 (10)	40.77 (10)	1.09 (17)
National Astronomical Observatory of Japan	Japan	1,852	54.55 (10)	40.77 (10)	.93 (21)
Max-Planck-Institut für Extraterrestrische Physik	Germany	1,657	54.38 (12)	40.71 (12)	1.37 (9)
Max-Planck-Institut für Astronomie	Germany	1,489	54.05 (13)	40.66 (13)	1.47 (7)
Australian National University	Australia	5,832	53.39 (14)	40.58 (14)	1.29 (10)

The institutions are sorted by degree measure

If extending the analysis out to the top fifty central actors, we find that relatively central institutions are spread across different countries and regions of the globe (see Appendix A in Supplementary material). In addition to the three international organizations: ESO, NOAO, and European Space Agency (ESA), there are twenty-nine in European countries (Austria, Denmark, France, Germany, Netherlands, Poland, Russia, Italy, Spain, Sweden, Switzerland, and the U.K.), twelve in countries of North and South America (Canada, Chile, Mexico, and the U.S.), four in Asian countries (China, Israel, and Japan), and three institutions in Oceania (Australia). Only one institution, the South African Astronomical Observatory (SAAO), is in Africa. Despite the geographic diversity of these central institutions, it is intriguing to note that the top ten actors, except for NOAO and the Chinese Academy of Sciences, are all from European countries. They are mostly European Union (EU) member states, such as Austria, France, Germany, Italy, Spain, and the U.K. This finding supports our belief that cross-national political coalition is influential on international collaboration networking. There are particularly many regional projects and academic societies amongst European institutions, creating a positive atmosphere for international collaboration.

Table 5 shows that Germany has the largest number of institutions (seven actors) in the top-fifty list, followed by the U.S. (six actors), France (five actors) and the U.K. (five actors). Although representing the second highest number, the U.S. institutions do not hold outstanding ranking places in terms of network centrality. The most prominent institution is the Harvard-Smithsonian Center for Astrophysics (CfA), which ranks 25th for degree and closeness centrality. Another famous institute, the National Aeronautics and Space Administration (NASA), has a moderate level of centrality relative to other central

Table 5 Distributions of country for top 50 central institutions, 2001–2009

Country	Region	Number of institutions	Rank of central position (in the top 50)		
			Degree	Closeness	Betweenness
Germany	Europe	7	12th, 13th, 17th, 22nd, 31st, 38th, 49th	12th, 13th, 17th, 22nd, 31st, 38th, 49th	9th, 7th, 23rd, 24th, 25th, 30th
U.S.	America	6	25th, 32nd, 34th, 40th, 41st, 47th	25th, 32nd, 34th, 39th, 41st, 46th	27th, 30th, 38th, 43rd, 48th
France	Europe	5	3rd, 23rd, 28th, 30th, 43rd	3rd, 23rd, 27th, 30th, 43rd	4th, 28th, 39th, 49th, 50th
U.K.	Europe	5	7th, 25th, 35th, 39th, 46th	7th, 25th, 35th, 40th, 46th	8th, 15th, 33rd, 42nd, 43rd
Canada	America	4	16th, 19th, 36th	16th, 19th, 36th	11th, 13th, 37th, 46th
International		3	2nd, 5th, 8th	2nd, 5th, 8th	2nd, 5th, 16th
Australia	Oceania	3	14th, 23rd, 45th	14th, 23rd, 45th	10th, 20th, 26th
Netherlands	Europe	3	15th, 20th, 42nd	15th, 21st, 42nd	12th, 19th, 41st
Spain	Europe	2	9th, 10th	9th, 10th	18th, 17th
Japan	Asia	2	10th, 27th	10th, 27th	14th, 21st
Italy	Europe	1	1st	1st	1st
Russia	Europe	1	3rd	3rd	3rd
China	Asia	1	6th	6th	6th
Mexico	America	1	18th	18th	29th
Denmark	Europe	1	20th	20th	35th
Switzerland	Europe	1	29th	29th	22nd
Poland	Europe	1	33rd	33rd	40th
Austria	Europe	1	[not in the top 50]	[not in the top 50]	34th
Israel	Asia	1	37th	37th	36th
Chile	America	1	44th	44th	45th
Sweden	Europe	1	48th	48th	47th
South Africa	Africa	1	50th	50th	[not in the top 50]

The table is first sorted by the number of institutions then by the best centrality ranking value

institutions, ranking at 32nd place in terms of degree and closeness centrality. They are followed by the other four U.S. institutions: California Institute of Technology (Caltech), the Space Telescope Science Institute (STScI), the University of Arizona, and the University of California at Berkeley. These six U.S. institutions all have high research productivity (>2,000 papers for the 9 years) but do not show strikingly high scores in the centrality measures. This observation may be accounted for by the nation with abundant resources in professional manpower and technology making these U.S. institutions popular collaborators in research. Yet for scientists there, they can accomplish research independently or domestically and do not necessarily reply on international collaborations. Unlike the U.S., there is only one organization with a high ranking place in Italy (Istituto Nazionale di Astrofisica), one in Russia (Russian Academy of Sciences), and one in China (Chinese Academy of Sciences). It is shown that national academies and institutes play a very important role in connection with external astronomical research organizations for

these three countries. The institutions dominate the domestic scene as well as the whole international collaboration network.

This study, on the other hand, illustrates peripheral and isolated actors in the network. Some institutions with a very low level of centrality measures are apparently located in the periphery of the network. The list is too long to be enumerated, although special cases with zero value of betweenness centrality can still be given to the Academy of Sciences of the Republic of Tajikistan, Boğaziçi Üniversitesi (Turkey), Brandeis University (USA), Duke University (USA), the Hungarian Astronomical Association, Universidade Estadual Paulista (Brazil), the University of Memphis (USA), the University of Regina (Canada), and Whitman College (USA). These institutions link with single or very few foreign partners, and thus cannot be intermediaries in international collaborative relationships. It is proper to define them as peripheral actors in the network. As for isolated actors, the Japan Meteorological Agency (JMA) is the only institution that is separated completely from others during the past 9 years. There is no connection between this institution and any other foreign counterpart in the collaboration network.

Dynamics of institutions' position in the international collaboration network

This study investigates the changes of institutions' positions in the network to learn more about the dynamics of the international collaboration network in astronomy and astrophysics. It explores how an actor's centrality ranking varies with time as well as what the changes of very central and peripheral actors are during the investigation periods. Both general features and special cases are discussed in this section. It is noticed that this study demonstrates an institution's dynamic position by actors' centrality ranking, instead of centrality scores, taking account of inherent rising level of centrality over time. There is an understanding that an institution with increasing centrality scores is not necessarily located as centrally as it has been because its network position is relative to other actors within the network.

Overall, an astronomical institution's network position varies with time. Almost all the institutions have more or less different ranking positions over the three periods, except for INAF, which has remained ranked at the 1st place for the three centrality measures. To demonstrate what dynamic patterns of institutions' positions are exhibited, this study categorizes the changes of an actor's centrality ranking into four types: (a) continually rising, (b) first rising then falling, (c) first falling then rising, and (d) continually falling. It shows that there is a roughly even proportion of each type of changes, especially in degree and closeness centrality. No single pattern overwhelmingly dominates the dynamic formation of the network. Among the 606 institutions, about 21 % of them hold a rising ranking place in degree and closeness centrality (20.79 % in degree and 20.96 % in closeness centrality) throughout the three periods, while an opposite trend is found for 23 % of the institutions (22.98 % in both degree and closeness centrality). For those that did not present continually rising or falling trends, there is an approximately equal frequency in the two categories of "first rising then falling" (28.38 % in degree and 27.89 % in closeness centrality) and "first falling then rising" (28.22 % in degree and 28.55 % in closeness centrality). Unlike from the results of degree and closeness centrality measures, the highest proportion here is accounted for by the "continually falling" category, with betweenness centrality of 36.96 %, indicating that for many institutions, their intermediary influence on the network diminished over time.

Although most institutions have experienced changes in centrality ranking position, not all of them present considerable changes over the investigation periods. According to

Table 6 Distribution of the types of changes in centrality ranking position

Type	diff. > 50		diff. > 100		diff. > 150		diff. > 200	
	N	%	*N*	%	*N*	%	*N*	%
Degree centrality								
Continually rising[a]	68	11.22	31	5.12	13	2.15	6	.99
First rising then falling	92	15.18	40	6.60	9	1.49	3	.50
First falling then rising	92	15.18	49	8.09	14	2.31	7	1.16
Continually falling[b]	77	12.71	30	4.95	9	1.49	4	.66
Total	329	54.29	150	24.75	45	7.43	20	3.30
Closeness centrality								
Continually rising[a]	73	12.05	38	6.27	19	3.14	8	1.32
First rising then falling	92	15.18	41	6.77	23	3.80	3	.50
First falling then rising	102	16.83	43	7.10	19	3.14	4	.66
Continually falling[b]	87	14.36	36	5.94	11	1.82	4	.66
Total	354	58.42	158	26.07	72	11.88	19	3.14
Betweenness centrality								
Continually rising[a]	46	7.59	16	2.64	5	.83	1	.17
First rising then falling	98	16.17	37	6.11	19	3.14	7	1.16
First falling then rising	93	15.35	47	7.76	28	4.62	10	1.65
Continually falling[b]	60	9.90	18	2.97	6	.99	2	.33
Total	297	49.01	118	19.47	58	9.57	20	3.30

$N = 606$. The variations of ranking positions are present either in the first (from 2001–2003 to 2004–2006) or in the second interval (from 2004–2006 to 2007–2009)

[a] The type includes institutions with first constant and then rising ranking positions and those with first rising and then constant ranking positions

[b] The type includes institutions with first constant and then falling ranking positions and those with first falling and then constant ranking positions

Table 6, around 50–60 % of institutions once had variations of over 50 ranking positions in the centrality ranking (54.29 % in degree, 58.42 % in closeness, and 49.01 % in betweenness centrality), while the others 40–50 % exhibited small or moderate changes in the ranking. About one-fifth to one-quarter of institutions (24.75 % in degree, 26.07 % in closeness, and 19.47 % in betweenness centrality) presented a variation of over 100 ranking positions. When setting a higher threshold for differences, the study shows that only three percent of institutions have dramatic changes of over 200 ranking positions in each measure of centrality.

In general, an astronomical institution's centrality ranking position in the international collaboration network varies with time. Nevertheless, for many institutions, notable changes take place only once during the periods. Of those which show a variation of 50 ranking positions, nearly one-third of institutions (106 of 329 in degree, 113 of 354 in closeness, and 99 of 297 in betweenness centrality) maintain such variations for successive periods. Only a few continuously exhibit a considerably large change. There are seven organizations which exhibit a variation of more than 150 ranking positions over time: the Abdus Salam International Centre for Theoretical Physics (ICTP) in Italy, Ege Üniversitesi in Turkey, the Real Instituto y Observatorio de la Armada in Spain, Seoul National University in Korea, Toyama University in Japan, the Université de Nice Sophia Antipolis

in France, and Uttar Pradesh State Observatory in India. Among them, ICTP is viewed as the most dynamic actor in the network, demonstrating substantial changes in all three centrality rankings (from 483rd to 204th and to 420th in degree centrality, from 476th to 237th and to 487th in closeness centrality, and from 406th to 233rd and to 424th in betweenness centrality) throughout all three periods.

The study demonstrates the dynamic network of international collaboration in astronomical community by analyzing the change of central institutions, moreover. Compared with those of the 9 years from 2001 to 2009, there are 23 institutions newly present in the top-fifty lists for the three periods (see Appendix B in Supplementary material for the complete lists for each period).[2] They appear in the lists for a short-term period but are not included in the top group for the nine-year data span. Besides, the top central institutions do not keep in the same ranking positions. Variations can be observed from certain specific cases in the top-fifty list of central actors. Some institutions have moved from a central to a relatively peripheral position (with a ranking position behind the 100th), while some others display opposite changes in centrality. In Table 7, the Swinburne University of Technology and Universität Bonn show a major rise in degree and closeness centrality rankings. In contrast, the Space Research Organization Netherlands, the Isaac Newton Group of Telescopes, and Consiglio Nazionale delle Ricerche (CNR) continued to exhibit falling rankings in these two centrality indices.

Table 7 indicates that the list of central institutions with variations in betweenness centrality is largely different from those of degree and closeness centrality. It contains a larger number of actors than the lists of the other two measures and shows different patterns of changes in central positions. While there are apparent improvements in the rankings of the Korea Astronomy and Space Science Institute, McGill University, and the Max-Planck-Institut für Sonnensystemforschung, an obvious decline is found in the Space Research Organization Netherlands, the Isaac Newton Group of Telescopes, the University of Texas at Austin, Göteborgs Universitet, and CNR. Some other institutions experienced fluctuations in centrality ranking; the Academy of Sciences of the Czech Republic, the University of Southampton, and Universiteit Utrecht have first rising and then falling ranking positions, yet the Max-Planck-Institut für Kernphysik, Universität Hamburg and the Krakow Pedagogical University present the opposite.

Among the central institutions placed in the top fifty, the Italian organization, CNR, has experienced the most dramatic variation in network position. It is placed in the center with a ranking position of 17th in 2001–2003 and 65th in 2004–2006, but later becomes a peripheral character at 301st in 2007–2009 in terms of degree centrality. A similar finding applies to closeness (from 17th to 65th and then to 275th) and betweenness centrality (from 18th to 37th and then to 350th). Looking back at the institution's history, we find that this downtrend can be attributed to a change that seven astronomical institutes formerly affiliated with CNR have been merged into INAF around 2005. This merger does not seem

[2] Five institutions, including Imperial College London, the Swinburne University of Technology, the Universidad de Chile, the Universidade do Porto, and the University of Hertfordshire, are newly appeared in the lists of degree and closeness centrality. One institution, the University of Texas at Austin, is newly appeared in the lists of closeness and betweenness centrality. Twelve institutions, including Göteborgs universitet, the Istituto Nazionale di Fisica Nucleare, Korea Astronomy and Space Science Institute, Krakow Pedagogical University, M.V. Lomonosov Moscow State University, the Max-Planck-Institut für Kernphysik, the Max-Planck-Institut für Sonnensystemforschung, South African Astronomical Observatory, the Universität Hamburg, the Universiteit Utrecht, the University of Leeds, and the University of Southampton, are newly appeared in the list of betweenness centrality. Five institutions, including CNR, Durham University, the Isaac Newton Group of Telescopes, Johns Hopkins University, and the Space Research Organization Netherlands, are newly appeared in the lists of degree, closeness, and betweenness centrality.

Table 7 Central institutions with significant variation of 50 ranking positions

Institution	2001–2003		2004–2006		2007–2009	
	Scores	(rank)	Scores	(rank)	Scores	(rank)
Degree centrality (normalized)						
Swinburne University of Technology	8.264	(191)	17.686	(88)	32.231	(40)
Universität Bonn	13.058	(112)	25.455	(46)	30.248	(45)
Space Research Organization Netherlands	20.826	(45)	18.678	(78)	20.661	(103)
Isaac Newton Group of Telescopes	21.157	(43)	19.835	(72)	19.504	(115)
Consiglio Nazionale delle Ricerche	28.926	(17)	21.653	(65)	7.438	(301)
Closeness centrality (normalized)						
Swinburne University of Technology	3.336	(196)	4.381	(89)	5.658	(42)
Universität Bonn	3.347	(101)	4.398	(48)	5.654	(45)
Space Research Organization Netherlands	3.358	(44)	4.381	(87)	5.618	(111)
Isaac Newton Group of Telescopes	3.358	(44)	4.386	(73)	5.616	(118)
Consiglio Nazionale delle Ricerche	3.369	(17)	4.389	(65)	5.570	(275)
Betweenness centrality (normalized)						
Academy of Sciences of the Czech Republic	.239	(97)	.144	(142)	1.153	(18)
University of Southampton	.475	(57)	.172	(125)	.709	(40)
Korea Astronomy and Space Science Institute	.045	(230)	.547	(52)	.702	(42)
McGill University	.104	(167)	.292	(84)	.619	(47)
Max-Planck-Institut für Sonnensystemforschung	.071	(197)	.212	(110)	.604	(49)
Universiteit Utrecht	.541	(49)	.060	(213)	.318	(81)
Space Research Organization Netherlands	.557	(47)	.429	(59)	.214	(102)
Max-Planck-Institut für Kernphysik	.169	(120)	.583	(48)	.208	(104)
Universität Hamburg	.284	(92)	.675	(41)	.187	(111)
University of Texas at Austin	.624	(43)	.334	(78)	.160	(126)
Krakow Pedagogical University	.191	(109)	.624	(46)	.134	(138)
Isaac Newton Group of Telescopes	.530	(50)	.185	(117)	.132	(141)
Göteborgs universitet	.577	(45)	.104	(174)	.084	(177)
Consiglio Nazionale delle Ricerche	1.255	(18)	.712	(37)	.008	(350)

The institutions are sorted first by scores/rank of 2007–2009 then by 2004–2006 and 2001–2003

to have caused striking changes for INAF, which has been placed in the most central position since the first period. For CNR, however, its centrality in the international collaboration network has been greatly affected by the reorganization policy.

Notwithstanding the variations mentioned above, it is found that institutions with the highest centrality ranking positions are more likely to remain in the core of the network. As shown in Table 8, the most notable actors, INAF and ESO, maintained their prominence throughout the three investigation periods. The Observatoire de Paris-Meudon, the Russian Academy of Sciences, NOAO and the University of Cambridge also stayed in top ten for the three centrality measures in all three time periods. By contrast, some other institutions show a more dynamic pattern in central position. For example, the Instituto de Astrofísica de Canarias and the Chinese Academy of Sciences have gradually moved to a more central position in the network, while the European Space Agency's centrality ranking position has descended with time.

Table 8 Institutions with highest centrality in the network, by period

Institution	2001–2003		2004–2006		2007–2009	
	Scores	(rank)	Scores	(rank)	Scores	(rank)
Degree centrality (normalized)						
Istituto Nazionale di Astrofisica	57.521	(1)	63.140	(1)	68.099	(1)
European Southern Observatory	48.760	(2)	55.537	(2)	59.008	(2)
Observatoire de Paris-Meudon	39.174	(4)	41.653	(5)	50.909	(3)
Instituto de Astrofísica de Canarias	30.744	(12)	36.364	(11)	46.942	(4)
Chinese Academy of Sciences	26.612	(24)	36.694	(10)	45.620	(5)
Russian Academy of Sciences	39.008	(5)	42.645	(4)	44.298	(6)
National Optical Astronomy Observatory	40.496	(3)	42.810	(3)	43.802	(7)
Consejo Superior de Investigaciones Científicas	30.744	(12)	39.174	(7)	43.471	(8)
Max-Planck-Institut für Extraterrestrische Physik	36.033	(7)	34.050	(15)	42.975	(9)
University of Cambridge	37.521	(6)	39.504	(6)	42.810	(10)
National Astronomical Observatory of Japan	28.264	(18)	34.876	(14)	42.810	(10)
Max-Planck-Institut für Astronomie	28.264	(18)	38.182	(8)	42.314	(12)
Australian National University	32.397	(9)	37.355	(9)	38.843	(15)
European Space Agency	35.702	(8)	36.033	(13)	37.190	(22)
Closeness centrality (normalized)						
Istituto Nazionale di Astrofisica	3.403	(1)	4.477	(1)	5.782	(1)
European Southern Observatory	3.393	(2)	4.462	(2)	5.753	(2)
Observatoire de Paris-Meudon	3.381	(4)	4.434	(5)	5.725	(3)
Instituto de Astrofísica de Canarias	3.371	(12)	4.422	(11)	5.712	(4)
Chinese Academy of Sciences	3.366	(23)	4.423	(9)	5.708	(5)
Russian Academy of Sciences	3.381	(4)	4.436	(3)	5.704	(6)
National Optical Astronomy Observatory	3.383	(3)	4.436	(3)	5.702	(7)
Consejo Superior de Investigaciones Científicas	3.371	(12)	4.428	(7)	5.701	(8)
National Astronomical Observatory of Japan	3.368	(18)	4.420	(14)	5.698	(9)
University of Cambridge	3.379	(6)	4.429	(6)	5.697	(10)
Max-Planck-Institut für Extraterrestrische Physik	3.377	(8)	4.419	(15)	5.697	(10)
Max-Planck-Institut für Astronomie	3.367	(21)	4.425	(8)	5.694	(12)
California Institute of Technology	3.372	(10)	4.415	(17)	5.682	(16)
Australian National University	3.374	(9)	4.423	(9)	5.681	(18)
European Space Agency	3.378	(7)	4.421	(12)	5.680	(21)
National Aeronautics and Space Administration	3.372	(10)	4.416	(16)	5.680	(21)
Betweenness centrality (normalized)						
Istituto Nazionale di Astrofisica	8.202	(1)	7.070	(1)	7.290	(1)
European Southern Observatory	4.406	(3)	4.676	(2)	3.231	(2)
Observatoire de Paris-Meudon	2.636	(5)	2.798	(3)	2.893	(3)
Chinese Academy of Sciences	1.300	(17)	1.566	(12)	1.987	(4)
Max-Planck-Institut für Radioastronomie	.842	(35)	.795	(34)	1.884	(5)
National Optical Astronomy Observatory	3.408	(4)	2.631	(5)	1.871	(6)
Russian Academy of Sciences	4.543	(2)	2.687	(4)	1.724	(7)
Instituto de Astrofísica de Canarias	1.101	(23)	1.151	(19)	1.638	(8)
University of Cambridge	2.470	(6)	1.682	(8)	1.554	(9)

Table 8 continued

Institution	2001–2003		2004–2006		2007–2009	
	Scores	(rank)	Scores	(rank)	Scores	(rank)
Max-Planck-Institut für Extraterrestrische Physik	2.104	(7)	1.359	(17)	1.409	(11)
Consejo Superior de Investigaciones Científicas	1.169	(21)	1.381	(14)	1.318	(10)
Australian National University	1.323	(16)	1.609	(10)	1.299	(13)
University of Toronto	1.644	(10)	1.601	(11)	1.176	(15)
Max-Planck-Institut für Astronomie	1.040	(25)	1.954	(6)	1.169	(17)
Harvard-Smithsonian Center for Astrophysics	.969	(27)	1.650	(9)	.944	(26)
California Institute of Technology	1.769	(9)	.990	(26)	.914	(27)
European Space Agency	1.778	(8)	1.371	(16)	.841	(32)
University of Tokyo	1.367	(15)	1.867	(7)	.712	(38)

The institutions are sorted first by scores/rank of 2007–2009 then by 2004–2006 and 2001–2003

As for institutions with no or little centrality, the study shows that the number of peripheral and isolated actors participating in the network decreased over the past nine years. In Table 9, there are 72 peripheral institutions with zero betweenness centrality in 2001–2003, and 28 of them are completely separated from other actors within the network. The numbers decline to 62 and 21, respectively, in 2004–2006. This decline continues for the next triennial period, down to 45 peripheral actors and 16 isolates in the network of 2007–2009.

A moderate number of institutions have continuously stayed in the very periphery over time. Slightly over half of peripheral or isolated institutions (61 of 114) placed in this position only once in the three periods. Among the 45 peripheral actors in 2007–2009, 30 institutions remained so for two or more successive periods. Another indication is shown in the number of isolated actors in 2007–2009, which shows that only three out of sixteen institutions had been identified as isolates in earlier years. The other 13 actors are merely present in the latest period.

Although many institutions change their status over time, certain actors tend to remain, whether continuously or intermittently, in the marginal and secluded area of the network. Among 62 peripheral actors in 2004–2006, about 70 % of them (44 institutions) retain their

Table 9 The number of peripheral and isolated institutions, by period

Measure	2001–2003	2004–2006	2007–2009
Number of peripheral institutions[a]	72	62	45
Presenting for one period		18	15
Presenting for two periods		44	18
Presenting for three periods			12
Number of isolated institutions	28	21	16
Presenting for one period		9	13
Presenting for two periods		12	2
Presenting for three periods			1

[a] The peripheral institutions are defined as actors with zero betweenness centrality. They include isolated ones that have no tie connecting them to any other actor (zero degree and closeness centrality)

positions for two successive periods. The other eighteen institutions are newcomers to this period. The proportion decreases to around 50 % (12 of 21 institutions) in terms of isolates, yet still shows an overlap in identified peripheral and isolated actors between two of the periods. Overall there are twelve institutions that hold peripheral or isolated position throughout all three periods. These organizations are the Academy of Sciences of the Republic of Tajikistan, Boğaziçi Üniversitesi, Brandeis University, Duke University, Goethe-Universität Frankfurt am Main, the Hungarian Astronomical Association, the Muséum National d'Histoire Naturelle, Union College, the Universidade Estadual Paulista, the University of Memphis, the University of Regina, and JMA.

The above results indicate that even though the centrality of most astronomical institutions varies with time, we do not expect radical changes in their network positions. A small proportion of institutions experienced a dramatic rise or fall in centrality ranking positions in the study periods. For these institutions, the changes may take place at infrequent intervals. Moderate variation can also be observed in the very center and periphery of the network. Despite the changes in centrality ranking positions, it is found that institutions placed in these areas tend to retain their status for long periods.

Conclusion

The astronomical research community is enthusiastically involved in collaborative research across multiple countries. However, a discrepancy exists among astronomical institutions in the international collaboration network. The centrality analysis in this study clearly indicates that astronomical institutions are located in different levels of positions embedded within the network. This supports previous literature on the differences of participants' access to a co-authorship network (Nagpaul and Sharma 1994; Newman 2004).

Among the 606 institutions investigated in the study, INAF, ESO, the Russian Academy of Sciences, the Observatoire de Paris-Meudon, and NOAO are the top five most central organizations. Although ranking differently across the three centrality measures (including degree, closeness, and betweenness centrality), they are at the core and accepted as the most popular, important, and influential institutions in the international collaboration network. As for peripheral and isolated actors, JMA is the only institution that did not connect with any foreign partners during the 9 years.

The observation of the most central actors gives us a clue that large, famous institutions are more likely to be popular, important, and influential participants in international collaboration. International organizations, such as ESA, ESO, and NOAO, and national academies and research councils of large countries, such as RAS (Russia), CAS (China), and CSIC (Spain), have high centrality ranking positions. The most central institutions, furthermore, are mostly concentrated in European countries. This is in accord with the findings of other researchers, which pointed out volumes of scientific interaction existing between and among member states of EU (Geuna 1998; Glänzel et al. 1999; Leydesdorff 2000; Marshakova-Shaikevich 2006). In this regard, regional political cooperation is an influential factor in international collaboration.

It is noted that centrality in the international collaboration network does not always reflect an institution's reputation in astronomical community, in spite of the sense that central nodes are usually the most important actors in a network. Some world-famous astronomical institutions, such as CfA, NASA, and Caltech, have high research productivity but show no strikingly high scores in the centrality measures. This might be

accounted for by their domestic support and independence in research. They do not rely on international collaborations to accomplish astronomical research.

Regarding the characteristics varying with time, the study shows that generally most astronomical institutions have undergone some but not radical changes in their network positions. Although almost all organizations presented different orders of centrality ranking in the course of study, about half of them have once shown notable variation (diff. > 50) in centrality ranking position in the investigation periods of time. Institutions in the very center (e.g. INAF) and very periphery (e.g. JMA) of the network are particularly more likely to retain their positions over time. In contrast to the static cases, the International Centre for Theoretical Physics (ICTP) in Italy acts very dynamically in the expanding network. It demonstrates substantial up-and-down changes in all three centrality rankings throughout the three periods.

In the dynamic network, some institutions moved from central to relatively peripheral positions, while others went in the opposite direction. For example, the Swinburne University of Technology and Universität Bonn showed major rises in degree and closeness centrality rankings, yet the Space Research Organization Netherlands, the Isaac Newton Group of Telescopes, and Consiglio Nazionale delle Ricerche (CNR) continued to see their rankings fall in these two centrality indices. Various factors might affect the variation. For CNR, its downtrend can be accounted for by the reorganization policy implemented around 2005.

There is little dispute that central actors in the international collaboration network are often regarded as the most prominent institutions. However, this does not mean that organizations' administrators are encouraged to aggressively pursue multinational collaborations just in order to raise their centrality in the network. As mentioned above, an astronomical institution's network centrality is not necessarily positively correlated with its reputation. Several well-known organizations are not found in the very center of the network. It is certain, though, that the central institutions are actively in collaborations with various countries, and the number of foreign partners matters in demonstrating the prominence in the network.

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