Scientometric Portrait of Nobel Laureate S. Chandrasekhar

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S. Chandrasekhar, the well known Astrophysicist is widely recognised as a very successful Scientist. His publications were analysed by year, domain, collaboration pattern, channels of communications used, keywords etc. The results indicate that the temporal variation of his productivity and of the types of papers published by him is of such a nature that he is eminently qualified to be a *role model* for the younger generation to emulate. By the end of 1990, he had to his credit 91 papers in *Stellar Structure and Stellar atmospheres*. 80 papers in *Radiative transfer and negative ion of hydrogen*, 71 papers in *Stochastic, statistical hydromagnetic problems in physics and astronomy*, 11 papers in *Plasma Physics*, 43 papers in *Hydromagnetic and Hydrodynamic Stability*, 42 papers in *Tensor-virial theorem*, 83 papers in *Relativistic astrophysics*, 61 papers in *Mathematical theory of Black holes and colloiding waves*, and 19 papers of *general* interest.

The highest Collaboration Coefficient was 0.5 during 1983-87. Productivity coefficient was 0.46. The mean Synchronous self citation rate in his publications was 24.44. Publication density was 7.37 and Publication concentration was 4.34.

Keywords/Descriptors: **Biobibliometrics; Scientometrics; Bibliometrics; Collaboration; Individual Scientist; Scientometric portrait; Sociology of Science, History of Science.**

1. Introduction

Subrahmanyan Chandrasekhar was born in Lahore (then a part of British India) on 19 October 1910. He had his early education by private tution till he was twelve. He had his high school education in the Hindu High School, Triplicane during the years 1922-25. He had his University education at the Presidency College during 1925-30 and received his Bachelor's degree, B.Sc.(Hon.), in physics in June 1930. He was awarded a Government of India Scholarship for graduate studies in Cambridge, England in July 1930 to work in theoretical physics, more specifically in the theory of stellar structure, the field which was dominated then by Arthur Eddington.

He became a research student under the supervision of professor R. H. Fowler (who was responsible for his admission to Trinity College). On the advice of Professor P. A. M. Dirac, he spent his three undergraduate years at the Institute for Theoretisk Fysik in Copenhagen.

He was awarded Ph. D. degree by Cambridge University in 1933. He was elected as a fellow at Trinity College for the period 1933-37. He was a Research Associate at Yerkes Observatory, Chicago during 1936-38. He became Assistant Professor, Chicago University during 1938-41, Associate Professor (1942-43), Professor (1943-47), Distinguished Service Professor of Theoretical Astrophysics (1947-52), Morton D. Hull Distinguished Service Professor of Theoretical Astrophysics (1952-1986). He was Professor Emeritus (1986-95). He died of heart failure in Chicago on 21st August 1995.

He was an editor of the journal *Astrophysical Journal* during 1952 - 1971. When he took over, the journal was nothing more than a private journal of Chicago University. By the time he resigned it

had become an official journal of the American Astronomical Society.

There is no doubt that he was influenced by his illustrious uncle Sir C. V. Raman the Nobel Laureate for 1930 well known for his invention on *Raman Effect*.

Many honours and awards were bestowed on him in recognition of his contribution in the field of Astrophysics. Important ones being :

1. Fellow of the Royal Society of London - 1944.
2. Adams prize (Cambridge University) - 1947.
3. Bruce Medal of the Astronomical Society of the Pacific - 1952.
4. Gold Medal of the Royal Astronomical Society of London - 1952.
5. Elected to the National Academy of Sciences - 1955.
6. Rumford Medal of the American Academy of Arts and Sciences - 1957.
7. Srinivasa Ramanujan Medal of the Indian National Science Academy - 1962.
8. Royal Medal of the Royal Society - 1962.
9. National Medal of Science (United States) - 1968.
10. Padma Vibhusan Title (India) - 1968.
11. Henry Draper Medal of the National Academy of Sciences - 1971. Smoluchowski Medal (Polish Physical Society).
12. Dannie Heinemann Prize of American Physical Society - 1974.
13. Nobel Prize - 1983.
14. Dr. Tomalla Prize (ETH, Zurich).
15. Copley Medal of Royal Society -1984.
16. R. D. Birla Award - 1984.
17. Vainu Bappu Medal of the Indian National Science Academy - 1985.

He was also a member of following Academies :

- National Academy of Sciences
- American Academy of Arts and Sciences
- Royal Astronomical Society
- American Astronomical Society
- Royal Society

As a student Chandrasekhar had received as a prize, Eddington's famous book *The Internal Constitution of the Stars* which left a lasting impression on young Chandrasekhar's mind. This perhaps was responsible for his taking up research in the field of Astronomy and Astrophysics.

Chandrasekhar's contribution is particularly multi-faceted and covers many aspects of the evolution of stars. An important part of his work is a study concerning the problems of stability in different phases of their evolution. He has studied relativistic effects, which became important because of the extreme conditions which arise during the later stages of the star's development. One of Chandrasekhar's most well known contributions is his study of the *Structure of White Dwarfs*. In recent years he had worked on *The Mathematical Theory of Black Holes*.

His books : *An Introduction to the Study of Stellar Structure* (1939); *Principles of Stellar Dynamics* (1942); *Radiative Transfer* (1950); *Plasma Physics* (1960); *Hydrodynamic and Hydromagnetic Stability* (1961); *Ellipsoidal Figures of Equilibrium* (1969); *and The Mathematical Theory of Black Holes* (1983) have become classics in the fields of Astronomy and Space research.

He had wide interest in music and literature, and he wrote a book entitled *Truth and beauty : aesthetics and motivations in science*. His final book was a commentary on, *Newton's principia for the common reader*, published early 1995.

Chandrasekhar had to face several humiliating experiences in the hands of noted astronomers which did not dampen his zeal, spirit and scientific temper which was in him by birth.

It is noteworthy to mention that Chandrasekhar's students Tsung - Dao Lee and Chen Ning Yang were awarded Nobel prize in physics for 1957 at their age 31 and 35 respectively for their investigation of the so-called parity laws which led to the discoveries regarding elementary particles. S. Chandrasekhar was awarded Nobel prize jointly with A. Fowler for his contributions on the evolution of stars in 1983 when he was 73 years of age mainly for his well known discovery 'Chandrasekhar limit' named after him which states that *Some stars are too massive to become white dwarf star which is formed with mass greater than a limiting value (1.4 $M_\odot$)*.

The Nobel prize is regarded not only by laymen but also by scientists as the most honorific

recognition of scientific achievement. The prestige of the Nobel prize is so great that it enhances the standing of nations and institutions as well as the reputation of its *laureates* [1-3]. His works have been well documented [4-9].

Citation analysis of some important contributions of S. Chandrasekhar has already been carried out [10]. This study deals with six citation classics which have been identified based on the citations received to the papers of S. Chandrasekhar. These six papers received 53% of total 10,359 citations during the period under study and concluded that there is a high correlation in quantity, quality of works, citedness and receiving honours and awards.

2. Objectives

Objectives of present work are to highlight quantitative aspects of the research communications :

(a) authorship pattern,
(b) domainwise contribution,
(c) author productivity,
(d) use of channels of communication
(e) bibliographic characteristics of publications, and
(f) documentation of keywords from title

The main concept of working on individual scientist is to provide *Role Model Scientist* for younger generation of science graduates and post graduates who have become frustrated due to various reasons. To show them light or hope or new direction towards success. Success of others may teach many things to follow their path. The attempt however small, may prevent them to make suicide of their creativity, and channelise aggressive energies of youth towards constructive ideas [11].

A successful scientist is one who keeps on publishing his ideas or works. To be successful, capacity to communicate effectively and efficiently is most fundamental. Scientific communications have their own regime and regimentation crossing all political and geographical boundaries.

3. Methodology

Scientific publication, seems to provide the best available basis for measuring research output. One of the first writers to suggest scientific publication as a measure of research productivity was Nobel Laureate William Shokley [12] who was interested in measuring research.productivity among individual within a group by analysing their publications. A few studies have been recently published on individual scientists [10, 13-41].

Bibliographic details of the publications of S. Chandrasekhar were documented on cards from the list appended at the end of volume six of Selected papers of S. Chandrasekhar [42] and sorting was done as per requirements of the study.

Normal count procedure [43] was followed. Full credit was given to each author regardless of whether he happens to be the first or the last author. It is widely recognised that scientists all over the world look at their own papers exclusively in that way. Similarly titles of the articles were analysed and one score was alloted for each keyword, subject, journal, etc.

The degree of collaboration [44] in a discipline was defined as the ratio of the number of collaborative research papers to the total number of research papers published in the discipline during a certain period of time (Figure 3).

Vinkler [45] defined (Table - 3) Publication Density as the ratio of the total number of papers published to the total number of journals in which the papers were published, and Publication Concentration as the ratio in percentage of the journals containing half of the papers published to the total number of journals in which those papers were published during the period under study.

Sen and Gan [46] defined Productivity Coefficient as the ratio of 50 percentile age to the total productivity age.

Lawani [47] defined (Table - 8) Synchronous Self Citation rate :

$$\text{Synchronous rate} = \frac{\text{Self references in an article}}{\text{Total no. of references in an article}} \times 100$$

Frequency of keywords from the titles of the articles were recorded. Data obtained from above study were presented in tables and figures.

4. Results and Discussion

During 1928 - 1990 S. Chandrasekhar had published 380 research communications in the

following domains

A = Steller structure and stellar atmospheres
B = Radiative transfer and negative ion of hydrogen
C = Stochastic, Statistical hydromagnetic problems in physics and astronomy
D = Plasma physics
E = Hydromagnetic and hydrodynamic stability
F = Tensor - Virial theorem
G = Relativistic astrophysics
H = Mathematical theory of Black holes and colloiding waves
I = General

Table 1 shows author productivity and distribution of authors in various domains. The research group of S. Chandrasekhar has the credits of number of authorships in various domains : A(91), B(80), C(71), D(11), E(43), F(42), G(83), H(61), and I(19). Total number of authors in the research group were 48. Researchers and their authorships in collaboration with S. Chandrasekhar in Chronological order of their association (in first publication with S. Chandrasekhar) are depicted in Figure 1. Most active researchers and their contributions with S. Chandrasekhar were N. R. Lebövitz (22) and D. D. Elbert (15). Other active collaborators with S. Chandrasekhar and their contributions were B. C. Xanthopoulos (10), G. Münch (8), and F. H. Breen (6). Other collaborators having three papers each were 12, two papers each were 20, and single paper each were 28.

B. C. Xanthopoulos had collaborated with S. Chandrasekhar in the domain H only. D. D. Elbert had collaborated with him in the A, B, E, F and G, whereas N. R. Lebövitz had collaborated in the domains E, F, G and H.

Domainwise Collaboration of S. Chandrasekhar with his 47 Collaborators and their status of authorship in various domains is provided in Table - 2. S. Chandrasekhar had single authored papers in various domains as A(63), B(34), C(39), D(2), E(30), F(14), G(43), H(25) and I(17). He had collaborations in various domains as A(28), B(46), C(32), D(9), E(13), F(28), G(40), H(36) and I(2).

Table Author Productivity and Distribution of Authors in Various Domains

No. of papers	Domainwise Authorships									No. of Authors	Total No. of Authorships	Prominent Collaborators
	A	B	C	D	E	F	G	H	I			
	8	4				2	5	1	1	28	28	
2	5	7	4				4			10	20	
3				6				6		4	12	
6										1	6	Breen, F. H.
8										1	8	Münch, G.
10								10		1	10	Xanthopoulos, B. C.
					4	1	2			1	15	Elbert, D. D.
22						11	9	1		1	22	Lebovitz, N. R.
			55	5	36	28	63	43	18		380	Chandrasekhar, S.
Total	91	80	71	11	43	42	83	61	19	48	501	

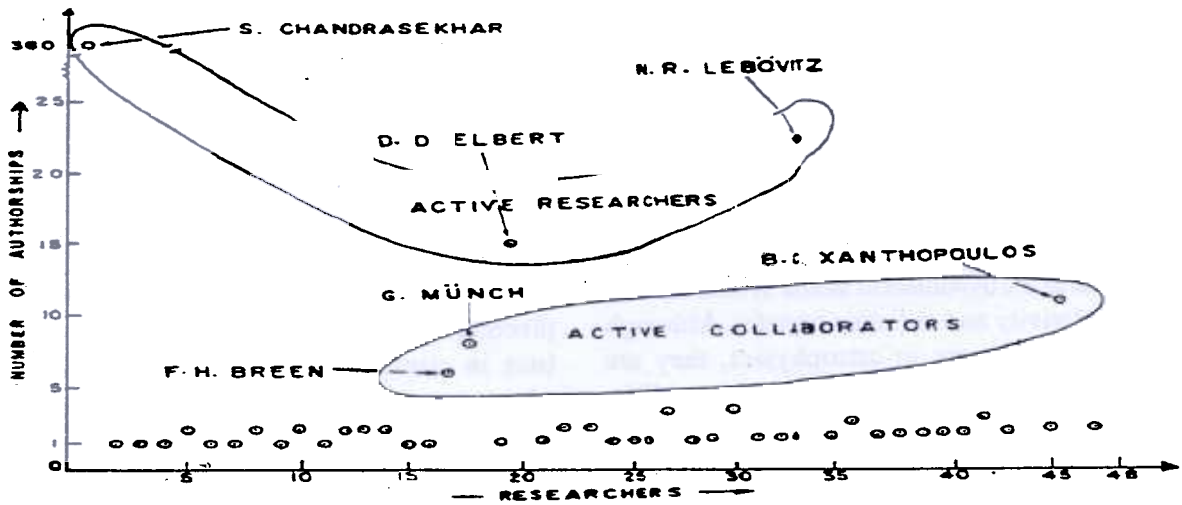

Fig. 1. Researchers Association in Chronological Order

Percentagewise contribution of authorships to various domains include A(18.16), G(16.57), B(15.97), C(14.17), H(12.18), E(8.58), F(8.38), I(3.79) and D(2.20).

He had published two papers in collaboration with the Nobel Laureate Enrico Fermi in the domain C during 1953.

His domainwise cumulative number of publications, his age, and scientific career advancements are depicted in Figure - 2.

A feature of Chandrasekhar's career was that he would write a very long series of papers in a particular research field and once he felt that he has exhausted everything in that particular field then he would summarise the whole work in the form of an authoritative monograph and then move on to another field.

It is clearly visible from the Figure - 2 that Chandrasekhar shifted his research domains very frequently. That is how he continued to remain very active in the field.

How does one not become an expert? Astrophysicist S. Chandrasekhar gave a remarkable television interview a few years ago.

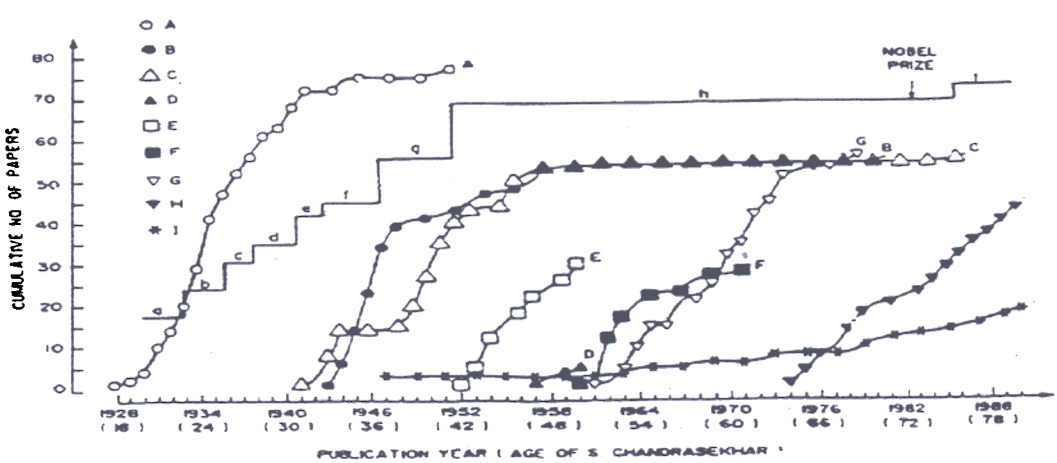

Fig. 2. Domainwise Publication Productivity of S. Chandrasekhar

Scientific Career Advanements : a = Govt. of India Scholar, Cambridge Univ.; b = Fellow, Trinity College, Cambridge Univ.; c = Res.Assoc., Yerkes Observatory, Chicago; d = Asst. Prof., Chicago Univ.; e = Assoc. Prof., Chicago Univ.; f = Prof., Chicago Univ., g = Disting. Sergice Prof. of Theoretical Astrophysics; h = Morton D. Hull Disting. Service Prof. of Theoretical Physics; i = Prof. Emeritus.

He had lead a Scientific Career notable for a rate of productivity that has not slowed down at all into his 70s. When asked how he has avoided the drop in creativity and productivity that plagues many scientists, he replied that approximately every seven years he takes up a new topic. He found that he would run out of new ideas after working in an area for too long. This pattern lead him to tackle such topics as the dynamics of stellar systems, white dwarfs, relativity and radiative transfer. Although all these subjects are in astrophysics, they are different enough to present unique problem [48].

With advances in research, vision of scientist expands, one island of superspecialisation or micro-theme expands and bridges connection with another island of micro-theme. A creative researcher travels through the bridges to other island and instead of returning to his original island such scientists continue to colonise and work on the latest theme of fresh interest due to intrinsic motivations which accelerate vigorous activities further and exploit new idea resources. Natives (Super Specialists) of that island (micro-theme) may have become complacent because of inbreeding of their thoughts. Creativity predominant in scientists is of two types: Convergent thinking creativity and Divergent thinking creativity [49].

The most productive researchers have changed research field more often than the less productive researchers [50].

However, no two individuals can be identical in their creativity i.e. each individual scientist has his/her own *Stereotype* [51] and *Mentor* [52-53]. Hence, attempts to generalise may fail.

With time and advances in research a creative scientist builds-up his/her own research team. As pioneer has already established himself he becomes pivote around whom entire team revolves in spirals (not in circle, because in circle there is no advancement as end meets the beginning) the direction and progressive movement of the spiral shifts its progress slowly to next higher stratum every time. Leader or conductor of the orchestra has the responsibility to bring forth best in every individual. Thus with advancing age many individuals and groups join such an individual for their own individual success as well as to satisfy affiliation needs.

Quinquennial publication productivity of S. Chandrasekhar is shown in Figure - 3. Highest Collaboration coefficient was 0.5 during 1983-87. His productivity coefficient was 0.46 which is clear indication of his high publication productivity behaviour during early period of 29 years of research publication career.

His first paper was published in 1928 in *Indian*

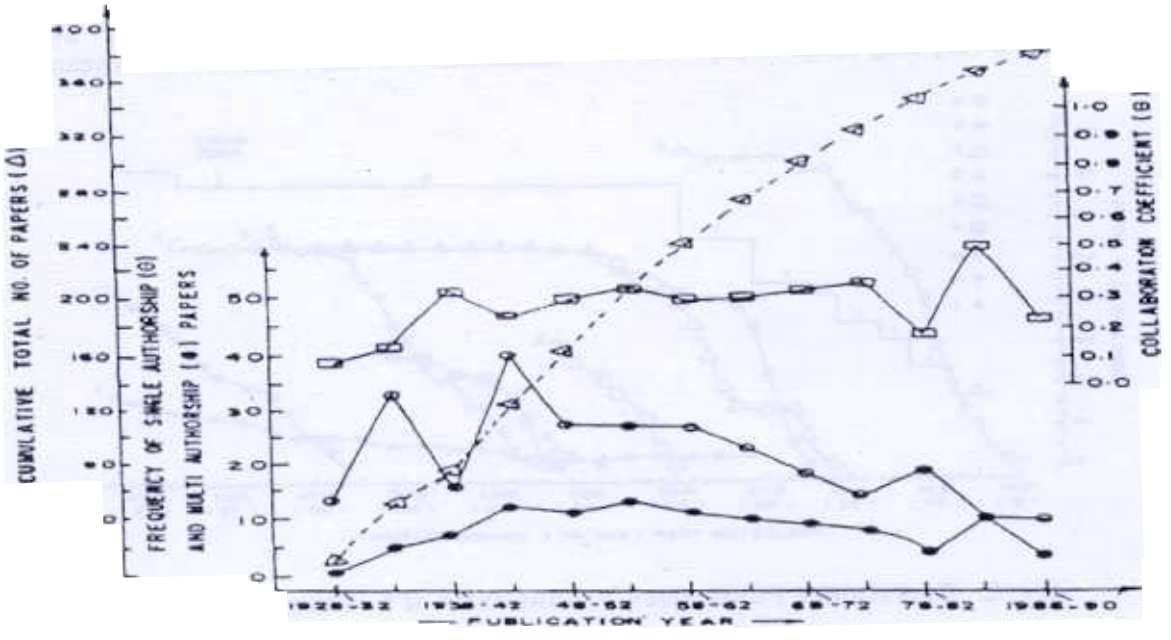

Fig. 3 Quinquennial Publication Productivity of S. Chandrasekhar

Journal of Physics at 18 years of his age in the domain A.

Distribution of his 339 publications were in 46 journals, 16 chapters in books, 16 conference proceedings and nine books.

Journalwise scattering of publications of S. Chandrasekhar in various journals is provided in Table - 3. He has published 139 papers in *The Astrophysical Journal*, 59 papers in *Proceedings of the Royal Society A*, 31 papers in *Monthly Notices of the Royal Astronomical Society*, 14 papers in *Proceedings of the National Academy of Sciences*. He has published 10 papers in the journal *Observatory*.

Table 3. Journalwise Scattering of Publications of S. Chandrasekhar

Sl. No.	Journal	No.of Papers	Percentage	Cumulative percentage	Period of Journal usage			SCI JCR 1992		Country of publication
					FPY	LPY	TOTAL	IF	II	
1.	Astrophys. J.	39	41.0	41.0	1931	1975	45	2.931	0.152	US
2.	Proc. Roy. Soc. A.	59	17.4	58.4	1929	1990	62	1.673	0.289	UK
3.	Month. Notic. Roy. Astron. Soc.	31	9.1	67.5	1931	1984	54	2.579	0.460	UK
4.	Proc. Natl. Acad. Sci.	14	4.1	71.6	1956	1963	8	10.480	1.436	US.
5.	Observatory	10	3.0	74.6	1933	1972	40	0.814	0.227	UK
6.	Philos. Mag.	9	2.7	77.3	1930	1957	28	-	-	UK
7.	Nature	7	2.1	79.4	1935	1990	56	22.139	5.224	UK
8.	Phys. Rev.		2.1	81.4	1949	1971	23			US
9.	Proc. Camb. Phil. Soc.	6	1.8	83.3	1935	1955	21			UK
10.	Zeit. Astrophys.	6	1.8	85.1	1931	1937	7	-		Gemany
11.	Rev. Mod. Phys.	5	1.5	86.6	1943	1949	7	14.071	1.759	US
12.	Science	4	1.2	87.8	1944	1981	38	20.967	3.600	US
13.	Am. J. Phys.	3	0.9	88.7	1969	1972	4	0.563	0.134	US
14.	Contemp. Phys.	3	0.9	89.6	1973	1980	8	1.541	0.111	US
15.	Ann. Phys.	2	0.5	90.1	1957	1958	4	0.608	0.509	UK
16.	Mathematika	2	0.5	90.6	1954	1957	4	0.694	0.000	UK
17.	Philos. Trans. Roy. Soc. London		0.5	91.1	1950	1952	3	182	0.237	UK
18.	Proc. Am. Philos. Soc.		0.5	91.6	1939	1964	26	-	-	US.
19.	Am. Math. Monthly		0.3	91.9	1954	1954		0.193	0.101	US
20.	Ann. New York Acad. Sci.		0.3	92.2	1943	1943		0.830	0.141	US
21.	Astrofisika		0.3	92.5	1988	1988				Russia
22.	Astron. J. Sov. Union		0.3	92.8	1934	1934				Russia
23.	Astrophys. Norvegic		0.3	93.1	1964	1964				Norway
24.	Bull. Am. Acad. Arts & Sci.		0.3	93.4	1989	1989				US
25.	Bull. Am. Math. Soc.	1	0.3	93.7	1947	1947		0.857	0.137	US

continued.

26. Can. J. Phys.		0.3	94.0	1951	1951		0.461	0.099	Canada
27. Commun.Pure Appl. Math.		0.3	94.3	1967	1967		1.080	0.167	US
28. Curr. Sci.		0.3	94.6	1985	1985		0.253	0.075	India
29. Ind. J. Phys.		0.3	94.9	1928	1928	1	-	-	India
30. J. Astrophys. Astron.		0.3	95.2	1984	1984		0.464	0.105	India
31. J. Ind. Math. Soc.		0.3	95.5	1960	1960		-	-	India
32. J. Math. Anal. Appl.		0.3	95.8	1960	1960		0.291	0.081	US
33. J. Math. Mech.		0.3	96.1	1961	1961				US
34. J. Ration. Mech. Anal.		0.3	96.4	1954	1954				US
35. Mem.Soc.Roy.Soc. deLiege		0.3	96.7	1935	1935				France
36. Nord. Astron. Tidskr.		0.3	97.0	1935	1935				Norway
37. Notes. Record. Roy. Soc		0.3	97.3	1976	1976				UK
38. Phys. Rev. Lett.	1	0.3	97.6	1965	1965				US
39. Physics Today		0.3	97.9	1971	1971				US
40. Proc. Am. Acad. Art. Sci.		0.3	98.2	1957	1957			-	US
41. Proc. Lond. Math. Soc.		0.3	98.5	1959	1959		0.649	0.188	UK
42. Pub. Astron. Soc. Pacific.		0.3	98.8	1952	1952		.047	0.006	France
43. Quart. J. Mech. Appl. Math.		0.3	99.	1955	1955		0.567	0.115	UK
44. Quart. J. Roy. Astron. Soc.		0.3	99.4	1980	1980		0.514	0.042	UK
45. Scientific Month.		0.3	99.7	1947	1947				US
46. Trans. Am. Philos. Soc.		0.3	100.0	1954	1954				US
Total	339								

FPY = First Paper Publishing Year; LPY = Last Paper Publishing Year IF = Impact Factor; II = Immediacy Index; IF and II values taken from SCI Journal Citation Reports 1992.

In the highest Impact Factor (22.139) journal *Nature* he has published seven papers. In other highest Impact Factor (20.967) journal *Science* he has published four papers: *Reviews in Modern Physics* having Impact Factor (14.017) where he has published five papers.

The journals from various countries publishing S. Chandrasekhar's research papers were : 21 from USA (45.65%), 13 from UK (28.26%), four from India (8.70%), whereas from France, Norway and Russia two each, and Canada and Germany one each.

Average Bradford multiplier was 3.46. Publication density was 7.37 and Publication concentration was 4.34.

The frequency and cumulative number of papers published journalwise is depicted in Figure - 4.

Keywords in the titles of the articles were counted. The data are provided in Tables 4 and 5. From the data it is revealed that the titles were very compact and expressive [54].

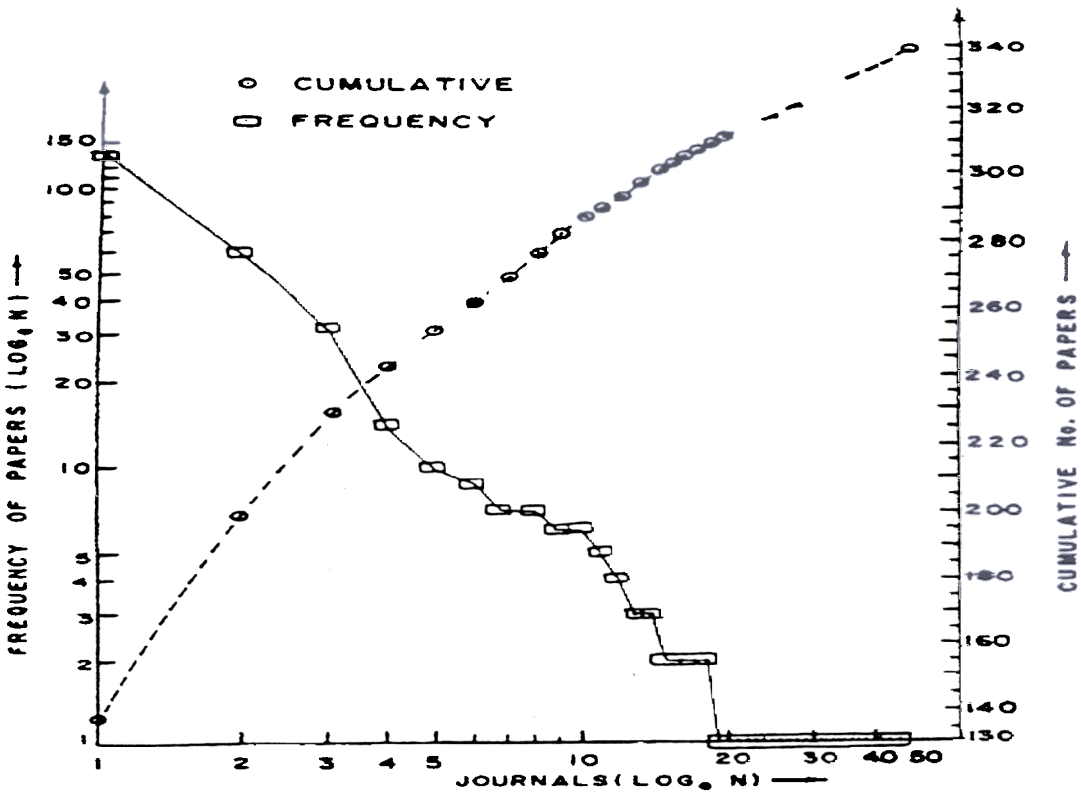

Fig. 4. Bibliograph on Papers of S. Chandrasekhar

Table 4. Length of Article Titles in Terms of Number of Keywords in the Titles of Publications of S. Chandrasekhar

No. of Keywords	No. of publications	Percentage
ONE	52	13.69
TWO	166	43.68
THREE	99	26.05
FOUR	40	10.53
FIVE	10	2.63
SIX	12	3.16
EIGHT	1	0.26

Table 5. Domainwise Keywords in the Titles of Research Papers of S. Chandrasekhar

Domain	Total No. of Words	Total No. of Keywords	Mean Per Title		Proportion of Keywords to No. of Words
			No. of Words	No. of Keywords	
A	623	166	8.09	2.16	3.75
B	470	115	8.55	2.09	4.09
C	513	140	9.33	2.55	3.66
D	39	12	7.80	2.40	3.25
E	412	110	11.44	3.06	3.75
F	283	81	10.11	2.89	3.49
G	781	200	12.40	3.17	3.91
H	459	112	10.67	2.60	4.10
I	102	28	5.67	1.56	3.64
	3682	964	84.06		33.64
	409.11	107	9.84		3.74

The Keywords frequencies in the titles of the papers is provided in Tables 6 and 7. High frequency Keywords were *Stability* (39), *General Relativity* (35), *Radiative equilibrium* (30), *Stellar atmosphere* (30), *Equilibrium* (26), *Magnetic fields* (17), *Stars* (17), *Gaseous masses* (9) *and Kerr black hole* (9).

Table 6. Keyword Frequencies in the Titles of Papers by S. Chandrasekhar.

Stability	39	Colloiding waves	6
General relativity	35	Dynamical friction	6
Radiative equilibrium	30	Gravitational waves	6
Stellar atmosphere	30	Hydrodynamics	6
Equilibrium	26	Interior of stars	6
Magnetic fields	17	Isotropic turbulence	6
Stars	17	Oscillations	6
Gaseous masses	9	Post-Newtonian effects	6
Kerr black hole	9	Thermal instability	6
Instability	8	Uniformly rotating bodies	6
Perturbation theory	8	Absorption coefficient	5
Rotating cylinders	8	Axisymmetric perturbations	
Fluctuations	7	Brightness	
Hydrodynamic stability	7	Deformed figures	
Negative hydrogen ion	7	Equations	5
Statistical theory	7	Gravitational perturbations	5
Stelar dynamics	7	Jacobi ellipsoids	5
Viscous flow	7		
Astronomy	6		
Axisymmetric systems	6		

continued.

Maclaurin spheroids	5
Milky way	5
Non-radial oscillations	5
Post-Newtonian approximation	5
Reissner - Nordstrom black hole	5
Stellar systems	5
Turbulence	5
Virial theorem	5
Distorted polytropes	4
Fluid motions	4
Gravitational field	4
Gravitational radiation	4
Gravitational stability	4
Hydromagnetics	4
Layer of fluid	4
Random distribution	4
Rotating gaseous masses	4
Stationary	4
Stellar configurations	4
Absorption	3
Absorption lines	3
Astrophysics	3
Beauty	3
Black holes	3
Coriolis force	3
Decay	3
Eddington. A. S.	3
Ellipsoidal figures	3
Force - free magnetic field	3
Four boundary conditions	3
Incompressible fluid	3
Ionization	3
Kerr geometry	3
Magneto hydrodynamics	3
Miline. Edward Arthur	
New statistics	3
Opacity	3
Planetary nebulae	3
Schwarzschild black hole	3
Science	
Stellar coefficient	3
Stellar mass	3
Stellar structure	3
Super potentials	
Time relaxation	
Uniformly rotating configuration	3
Universe	
Variable density	3
Adiabatic invariants	2
Axisymmetric turbulence	2
β Canis Majoris stars	2
Cauchy horizon	2
Clusters	2
Coaxial cylinders	2
Compton Scattering	2
Congruent Darwin ellipsoids	2
Conservation laws	2
Dedekind ellipsoids	2
Degeneration cores	2
Density	2
Differentially rotating configurations	2
Diffuse reflection	2
Distribution	2
Dynamical instability	2
Dynamical stability	2
Dynamics	2
Einstein	2
Evolution	2
Expansion of functions	2
Extended stellar atmospheres	
Fluid sphere	
Forces	
Functions Gn. $m^{(m)}$	
General variational principle	2
Homogeneous mass	2
Infinite homogeneous medium	2
Inhibition of convection	2
Internal motions	2
Invariant theory	2
Inviscid flow	2

continued.

Ionized gas	2	Radiative transfer	2
Kerr metric	2	Rate of escape	2
Low density	2	Reflexion	2
Magnetic rotation	2	Reversing layers of stars	2
Motions	2	Riemann ellipsoids	2
Negative oxygen ion	2	Rotating configurations	2
Neutrino waves	2	Rotating fluid sphere	2
Newtonian gravitation	2	Roche ellipsoids	2
Oort, J. H.	2	Schwarzschild limit	
Oxygen	2	Slow rotation	
Polarization	2	Solar chromosphere	2
Post-Newtonian equations	2	Sunlit sky	2
Pressure	2	Thermodynamics	2
Pulsation	2	Transmission	2
Pursuit of science	2	Viscous dissipation	2
Radial acceleration	2	White dwarfs	2

Table 7. Keywords Used Only Once in the Titles of Papers by S. Chandrasekhar

Absorbing atoms	Blanketing effect	Constitution of stars	Distorted polytropes
Absorption continuum	Blended absorption lines	Continuous spectrum	Distorted stellar configurations
Adjoining media	Boundary value problem	Convection	Double periods
Adjoint differential systems	Brownian motion	Coriolis acceleration	Double - star problem
Aeasthetics	Carter's theorem	Corona	Einstein's field equations
Amplifications	Central Radiation pressure	Correlation	Einstein Maxwell equations
Angular distribution	Central temperature	Cosmic magnetic fields	Einstein - Maxwell space times
Arbitrary spin	Centrally condensed stars	Cosmological constants	Einstein - Maxwell theory
Astrophysical conditions	Centrifugal force	Cowlirg's theorem	Einstein - Vacuum space times
Astrophysical interest	Characteristic value problems	Curved channel	Electromagnetic perturbations
Astrophysicist	Charged particles	Cylindrical impulsive waves	Electron
Atoms	Chromosphere	Cylindrical waves	Electron pairs
Axisymmetric gravitational fields	Collapsed configuration	Darwin ellipsoids	Elements
Asymmetric homogeneous dynamos	Collision	Degenerate cores	Ellipticity
Axisymmetric magnetic fields	Compton effect	Density distribution	Energies
Axisymmetric motions	Condensation of stars	Dirac, P. A. M.	Eridani B.
Beats	Configurations	Dirac, equation	
Bell - Szekers space time	Connective instability	Dirac's views	
Binary system	Constants	Dispersion	
		Dissociation formula	

continued.

Evolution of stars
Extended photospheres
Finite distance
Fluid conductor
Flux integral
Fourier - Bessel-type expansions
Fowler, Ralph Howard
Frequency
Galactic evidences
Gaseous star
Geodesics
Godel's Universe
Ground states of Helium
Ground states of Lithium ions
Ground states of oxygen ions
Hartree field
Heavy viscous fluid
Heisenberg's elementary theory
High order differenial equations
High speed atoms
Higher order virial equations
Highly collapsed configurations
Historical account
Homogeneous compressible model
Homogeneous ellipsoids
Homogeneous turbulent medium
Horizones
Human culture
Hydrogen atom
Hydromagnetic oscillations
Hyperbolic equations
Illumination
Integral equation
Integral theorem
Interface
Invariant theory
Ionization formula
Isothermal cores
Isothermal function
Isotopes
Isotropic scattering
Jacobi sequences
Jeans, janqes hopwood
Jeans sequences
Jeans spheroids
Lane - Emsden function θ 325
Limiting case
Limiting mass
Linear perturbations
Lindbald's theory
Liquids
Maclaurin sequences
Magnetic stars
Main sequence stars
Massless particles
Maxwell's equations
Metric perturbations
Motions of charged particles
Motivations
Moving atmosphere
Multiple frequencies
Nebular luminosity
Nebullium emission
Newtonian theory
Non-axisymmetric mode of oscillation
Non-dissipative couette flow
Non-stationary perturbed systems
Novae
Null dust
Nutku-Halil solution
Odd - parity mode
One-dimensional potential barriers
Onset of convection
Operation
Orthogonal functions
Otto struve
Outer layers
Pencil radiation
Perception of beauty
Perfect fluid
Perturbation analysis
Photographs
Physical content
Physical state of matter
Physical theory
Physics
Pin river
Pinch
Plane gravitational forces
Plane - parallel atmosphere
Plasma
Plasma physics
Post - Galilean transformation
2½ Post - Newtonian equation
Post - Newtonian methods
Post-Newtonian theory of Einstein
Potential barriers
Potentials
Probability distribution
Probability method
Prominences
Quasi normal modes
Radial ejection
Radial oscillation
Radial speed
Radiation reaction
Radial temperature gradient
Radiation
Rajagopal, C. T.
Rayleigh scattering
Recombination
Reflexion coefficients
Relative abundances
Relativistic degeneracy
Relativistic equilibrium
Relativistc instability
Relativistic statistics
Relativistic systems
Relativistic theory
Richtmyer
Roche model
Roots of
$J - (1 + ½) (\lambda n)J1+ ½ (\lambda)$
$J_1 + ½ (\lambda n) J - (\lambda + ½) N = 0$
Roots of
$Yn(\lambda n)\ Jn(\lambda) - Jn(\lambda n)\ Yn(\lambda) = 0$
Rotating liquid drops
Rotating stars
Rotational distortion
Rotational problem
Rotational velocities
Rotational masses
Rotating polytropes
Royal Astronomical Society
Rumford Medel Lecture 1957
Russel, H. N.
Scattering of radiation
Schwarzchild geometrics
Scientific attitude
Scientist

continued...

Second harmonic oscillations
Second post - Newtonian equations
Secular stability
Semi-infinite atmospheres
Sequence
Simultneous action
Singularities
Smart, W. M.
Softening of radiation
Solar research
Solar system origin
Source of energy
Spatial correlations
Speed of fluctuations
Spherical shells
Spiral arms
Spiral flow
Star - Streaming
State of matter
Stationary perturbed systems
Statistical basis
Statistical turbulence
Stellar absorption lines
Stellar encounters
Stellar envelops
Stellar evolution
Stellar models
Stellar photospheres
Stellar Scintillation
Stellar statistics
Stochastic problems
Stochastic variation
Strings
Sun
1' S State of helium
Temperatures
Tensor virial equations
Tensors of high rank
Terrestrial conditions
Teukolsky's equation
Teukolsky - Starbinsky constant
Thermal convection
Theoretical astrophysics
Theory of relativity
Third harmonics
Tidal distortion
Tidal problem
Time - scale
Time - like singularities
Total eclipse of the Sun
Transfer of radiation
Transformation
Transmission coefficients
Trumpler's stars
Truth and beauty
Two black holes
Two centre problem
Two commuting killing fields
Uniform rotation
Uniformly rotating fluid masses
Vacuum metrics
Variable viscosity
Variational methods
Velocity ellipsoid
Victor ambarstsumian
Virial equations
Virial relations
Viscid flow
Viscosity
Viscous liquid globe
Weizsacker theory
Weyl's solution
White dwarf configuration
White dwarf stars
Wolf - Rayet stars
X - functions
Y - functions

These keywords indicate his wide spectrum of interest, materials, methods, instruments used and subjects addressed to in the course of his 63 years of research paper publishing life span.

Domainwise bibliographic characteristics of publications of S. Chandrasekhar are provided in Tables 8 and 9.

It is evident from the publications of S. Chandrasekhar that they are full of Mathematical equations. It is very difficult for an ordinary reader to understand them very easily. One is awed by the depth of his physical acumen the range of his mathematical vision and the sweep of his astronomical knowledge. He was a confluence of Mathematician, Physicist and Astronomer in himself.

Highest number of equations per paper were 127.4 in the domain D, 108.3 in the domain B, and 107.4 in the domain H.

Table 8. Domainwise Bibliographical Characteristics per Publication of S. Chandrasekhar

Domain	No. of equations	No. of figures	No. of tables	Self citations	Citations to others	Synchronous self citation rate
A (N = 47)	46.5	1.6	2.1	0.8	6.3	11.14
B (N = 37)	108.3	2.0	1.5	1.9	7.6	20.23
C (N = 9)	84.8	1.0	1.0	2.0	8.8	18.46
D (N = 5)	127.4	0.8	0.4	0.8	5.8	12.12
E (N = 26)	57.7	1.7	1.9	3.3	4.9	40.57
F (N = 23)	88.8	1.3	2.7	4.9	4.8	50.00
G (N = 63)	61.7	0.6	0.5	3.9	5.1	43.02
H (N = 39)	107.4	3.0	0.3	4.0	7.1	36.32

Table 9. No. of Pages per Publication of S. Chandrasekhar

Domain	No. of pages
A (N = 74)	17.8
B (N = 55)	14.9
C (N = 55)	19.6
D (N = 5)	20.4
E (N = 35)	10.5
F (N = 27)	14.3
G (N = 62)	12.6
H (N = 42)	19.4

Numbers of figures per paper were three in the domain H and two in the domain B.

Number of tables per paper were 2.7 in the domain F, 2.1 in the domain A, 1.9 in the domain E, and 1.5 in the domain B.

Self citations per paper were 4.9 in the domain F, 4.0 in the domain H, 3.9 in the domain G and 2.0 in the domain C.

Citations to other authors per paper were 8.8 in the domain C, 7.6 in the domain B, 7.1 in the domain H, and 6.3 in the domain A.

Synchronous self citation rate for the domains were A (11.14), B (20.23), C (18.46), D (12.12), E (40.57), F (50.00), G (43.02), and H (36.32). Mean Synchronous self citation rate was 24.44 whereas mean synchronous self citation rates were for C. V. Raman (15.05) [29] and for K. S. Krishnan (13.82) [33]. This has sociological implications indicating that S. Chandrasekhar was a highly productive and key figure in his research speciality [47].

Number of pages per publication of S. Chandrasekhar are provided in Table 9.

India inspite of its limitations has produced so many illustrious scientists like H. J. Bhabha, J. C. Bose, C. V. Raman, S. Ramanujan, M. N. Saha and can produce so many scientists of high calibre provided it provides congenial scientific climate for scientists to work.

Chandrasekhar admits : he sometimes wonders how his career would have unfolded had he remained in India. Like Raman, his uncle, he might have presided over his own institute, but he then would have become enmeshed in the orcane politics of India's scientific establishment [9].

5. Conclusion

S. Chandrasekhar had contributed 380 papers during the period under study to various domains : *Stellar structure and Stellar atmospheres* (77); *Radiative transfer and negative ion of hydrogen* (55); *Stochastic, Statistical hydrodynamic problems in physics and astronomy* (55); *Plasma physics* (5); *Hydromagnetic and hydrodynamic stability* (36); *Tensor - Virial theorem* (28); *Relativistic Astrophysics* (63); *Mathematical theory of Black holes and Colloiding Waves* (43); and *General* (18).

He had 267 single authorship papers, 105 two authorship papers, and eight three authorship papers to his credit.

His 47 collaborators have contributed 421 authorships and domainwise collaborative authorships were A (28), B (46), C (32), D (9), E (13), F (28), G (40), H (36), and I (2).

He has published 139 papers in Astrophysical Journal, 59 papers in *Proceedings of Royal Society-A*, 31 papers in *Monthly Notices of Royal Astronomical Society*, 14 papers in *Proceedings of the National Academy of Sciences*, and 10 papers in *Observatory*.

High frequency keywords in the title of his papers were : Stability (39); General relativity (35); Radiative equilibrium (30); Stellar atmosphere (30); Equilibrium (30); Magnetic fields (17); Stars (17).

Mean bibliographic characteristics ranged : Equations (47-127); Figures (1-3); Tables (1-3); Self Citations (1-5); Citations to others (5-9); Synchronous Self Citation rate (11-50); Pages (11-20).

Considering all above bibliometric indicators, he represented excellence in his performance and had set up very high standards for his followers to surpass it. His work can be considered as performance of a Role Model Scientist to be emulated by present and future generations.

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Domainwise Collaboration

Sl. No.	Name	A			B						C			D				E						F			G			H			I			Total	Years		Total
		I	II		I	II		III			I	II		I	III			I	II		III			I	II		I	II		I	II		I	II			FPY - LPY	
			a	b		a	b	a	b	c		a	b		a	b	c		a	b	a	b	c		a	b		a	b		a	b		a	b			
1.	Chandrasekhar, S.	63	11	3	34	16	1	4			39	14	2	2	3			30	5		1			14	14		43	20		25	18	17	1			380	1928 - 1990	63
2.	Milne, E. A.			1																															1	1932 - 1932	1
3.	Moller, C. H. R.		1																																1	1935 - 1935	1
4.	Rosenfeld, L.			1																															1	1935 - 1935	1
5.	Swings, P.			2																															2	1936 - 136	1
6.	Beer, A.			1																															1	1936 - 1936	1
7.	Smart, W. M.			1																															1	1938 - 1938	1
8.	Henrich, Louis		1	1																															2	1941 - 1942	2
9.	Williamson, R. E.			1																															1	1941 - 1941	1
10.	Krogdahl, W.			1			1																												2	1942 - 1942	1
11.	Shonberg, M.		1																																1	1942 - 1942	1
12.	Von Neumann, J.												2																						2	1942 - 1943	2
13.	Cesco, C. V.								2																										2	1944 - 1945	2
14.	Sahade, J.									2																										2	1944 - 1945	2
15.	Wildt, R.						1																												1	1944 - 1944	1
16.	Hiltner, W. A.			1																															1	1945 - 1945	1
17.	Breen, F. H.						6																												6	1946 - 1948	3
18.	Munch, G.						1					1	6																						8	1946 - 1952	7
19.	Wares, G. M.						1																												1	1947 - 1947	1
20.	Elbert, D. D.			1			5		2											3		1			1			2							15	1951 - 1978	28
21.	Franklin, A.									1																										1	1952 - 1952	1
22.	Fermi, E.												2																						2	1953 - 1953	1
23.	Herzberg, E.						1			1																										2	1953 - 1955	3
24.	Limber, D. N.												1																						1	1954 - 1954	1
25.	Backus, G. E.											1																								1	1956 - 1956	1
26.	Pendergast, H.												1																							1	1956 - 1956	1
27.	Kaufman, A. A.																	3																		3	1957 - 1958	2
28.	Kendall, P. C.												1																							1	1957 - 1957	1
29.	Reid, W. H.																				1															1	1957 - 1957	1
30.	Watson, K. M.																	3																		3	1957 - 1958	2
31.	Woltjer, L.												1																							1	1958 - 1958	1
32.	Horak, H. G.					1																														1	1961 - 1961	1
33.	Wright, J. P.																											1								1	1961 - 1961	1
34.	Lebovitz, N. R.																						1					9			1					22	1961 - 1984	24
35.	Lee, L.																					1														1	1962 - 1962	1
36.	Contopoulos, G.																											2								2	1963 - 1967	5
37.	Roberts, P. H.																										1										1963 - 1963	1
38.	Tooper, R. F.																											1								1	1964 - 1964	1
39.	Lee, E. P.																										1									1	1968 - 1968	1
40.	Nutku, Y.																											1								1	1969 - 1969	1
41.	Esposito, F.																											1								1	1970 - 1970	1
42.	Friedman, J. L.																											2								2	1971 - 1973	3
43.	Miller, J. C.																											1								1	1974 - 1974	1
44.	Detweiler, S.																														3					3	1973 - 1977	3
45.	Weil, A.																																	1		1	1979 - 1979	1
46.	Xanthopoulos, B. C.																														10					10	1979 - 1989	11
47.	Hartle, J. B.																														1					1	1982 - 1982	1
48.	Ferrari, V.																														3					3	1984 - 1990	7
	Total	63	14	14	34	17	17	4	4		4	39	16	16	2	3	3	3	30	5	5	1	1	1	14	14	14	43	20	20	25	18	18	17	1	1	501		
Domainwise Authorship		91			80						71			11				43						42			83			61			19			501		
Percentage		18.16			15.97						14.17			2.20				8.58						8.38			16.57			12.18			3.79					

Stellar Structure and Stellar Atmospheres; B = Radiative Transfer and Negative Ion of Hydrogen; Relativistic Astrophysics; H = Mathematical Theory of Black Holes and of Colloiding Waves; General;
Stochastic, Statistical and Hydromagnetic problems in Physics and Astronomy; D = Plasma Physics; Single Author Papers; II = Two Author Papers; III = Three Author Papers; a = First Author; Second Author;
Hydromagnetic and Hydrodynamic Stability; F = Tensor - Virial Theorem pplications; Third Author; FPY = First Paper Published Year; LPY = Last Paper Published Year.