George Sudarshan: Perspectives and Legacy

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George Sudarshan has been hailed as a titan in physics and as one who has made some of the most significant contributions in several areas of physics. This article is an attempt to highlight the seminal contributions he has made in physics and the significant developments that arose from his work. Quanta 2021; 10: 75–104.

1 Introduction

Ennackal Chandy George Sudarshan (September 16, 1931 – May 13, 2018) was an Indian-American theoretical physicist and a professor at the University of Texas at Austin. He has made seminal contributions in a large number of research areas, which are listed in Table 1. His research activity spans a time period of six decades and a little more. In 2006 a Symposium on the Seven Science Quests of Sudarshan was held at Austin [1]. It brought out fairly comprehensively the progress made in these seven areas until then, subsequent to Sudarshan's path-breaking contributions. However there have been further developments in these areas as well as Tomography. Sudarshan's contributions in the areas of Foundations of Quantum Mechanics and Scattering theory have also been over a period of at least five decades, while his contributions to Quantum Computation span a couple of decades.

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2 Research Areas

Sudarshan's seminal contributions and a few of the research areas that they spawned are listed in Table 2. Comments on a few selected topics are given below.

2.1 V-A theory of weak interactions

Steven Weinberg declared that the Universal V-A theory of Weak Interaction of Sudarshan and Marshak was the key to the Electro-Weak Unification theory, for which he was awarded the 1979 Nobel Prize along with Abdus Salam and Sheldon Glashow. The latter theory then led to The Standard model in elementary particle physics which has stood the test of time, now for five decades. It may be of interest to note that the V-A (“vector” minus “axial vector”) theory was developed in 1957 by Sudarshan as part of his research [2–4] for a Ph. D. degree under the supervision of his mentor Robert Eugene Marshak. The first textbook on Particle Physics was written in 1961 by Marshak and Sudarshan, namely, *An Introduction to Elementary Particle Physics* [5].

2.2 Symmetries

Symmetries in Physics can be grouped into four areas: Classical Dynamics, Optics, Particle Physics and Quantum Mechanics. In Classical Dynamics, the application of Symmetries led to No-Interaction theorems [6, 7] and the group theoretic treatment of conventional classical dynamics resulted in his treatise with Mukunda, *Classical Dynamics: A Modern Perspective* [8, 9]. In Optics, the Gaussian and Fourier–Maxwell optics was developed,

Table 1: Seminal contributions of George Sudarshan.

Research Topic	Year
Symmetries in Physics	1955
V-A theory of Weak interactions	1957
Tachyons	1959, 1962
Quantum Mechanics: Foundations	1961
Scattering Theory	1961
Open Quantum Systems	1961, 1976
Quantum Optics	1963
Spin and Statistics	1968
Physics and Philosophy	1975
Quantum Zeno Effect	1977
Tomography	1980
Quantum Computation	2002

which in turn led to the development of electron optics. In Particle Physics, the $SU(2)$ Symmetry considerations led to sum rules between masses and magnetic moments of elementary particles [10, 11] which when extended to $SU(3)$ symmetry gave rise to the famous Gell-Mann–Okubo mass relationship and in Quantum Mechanics the study of geometric phases [12].

2.3 Spin-Statistics Theorem

Sudarshan believed strongly (some even dubbed it a “religious” belief) that a Non-Relativistic proof of the Spin-Statistics theorem [13, 14] should be possible. As early as 1968 he gave the non-relativistic proof in 3-dimensions and later extended it to higher dimensions [13–17]. Moo-Young Han who proposed with Yoichiro Nambu the Color symmetry of quarks [18], attributes this to the influence of Sudarshan’s belief in the validity of the Spin-Statistics theorem. Earlier Han had worked with Sudarshan as a research associate, which led to No-go theorems in combining internal symmetries with space-time theories.

2.4 Tachyons

Sudarshan has been described as an iconoclast in the sense that he did not hesitate to go against conventional wisdom if a fresh approach and a thorough investigation warranted it. It is this spirit that led him to show that the existence of particles traveling faster than light, now called tachyons [19, 20], did not violate any fundamental laws of physics. Since tachyons cannot manifest themselves as particles in the laboratory, it has not given rise to many further developments. However, there have been experimental results which claim to have detected tunneling effects faster than light. Tachyons have been exploited with greater success in Science fiction.

2.5 Quantum Coherence Optics

Sudarshan’s Diagonal Coherent Representation [21] was the first and correct theory to lay the foundation for the entire field of Quantum Optics [22]. This led to the observation of Antibunching and sub-Poisson statistics of photons, Squeezed states, Quantum Teleportation, to name but a few.

2.6 Quantum Zeno Effect

The Quantum analogue to the classical proposition of Zeno [23] was first proposed by Baidyanath Misra and Sudarshan. This has led to a vast array of research topics such as Decoherence, dissipation, Quantum Information, Quantum Technologies, Quantum control, etc.

2.7 Open Quantum Systems

The foundation for Open Quantum Systems was laid by Sudarshan, P. M. Mathews and Jayaseetha Rau [24], where they introduced the concept of dynamical maps describing the finite time evolution of open evolution of a system of interest interacting with a reservoir. Later on, the continuous time evolution was discussed in [25] which is now known as the GKSL (Gorini–Kossakowski–Sudarshan–Lindblad) equation.

2.8 Tomography

This is a burgeoning field. Sudarshan and his collaborators, mostly from Italy and Spain, have made and continued to make significant contributions on this and related topics [26, 27]. I think that it may be of interest to add probably a little known fact. Sudarshan’s first piece of work in Tomography was in Industrial application, namely in the development of CITA (Computerized Industrial Tomographic Analyzers) systems, along with a couple of colleagues in Physics at the University of Texas. They even got a couple of patents [28, 29] for it. However, it was the Radon transform involved in it, that caught his attention and interest, which he later used in physics problems [30].

2.9 Quantum Mechanics

Sudarshan’s contributions to the Foundations of Quantum Mechanics have spanned a period of five decades or more. In the last ten years of his life he had revisited the problem of Time as a dynamical variable [31], Uncertainty relations [32], CPT theorem [33], Scattering theory and Quantum computation.

Table 2: Areas of further development and research.

Research Topic	Developments
Symmetries in Physics	Classical Dynamics: No interaction theorems Optics: Gaussian, Fourier-Maxwell Optics, Electron Optics Particle Physics: Masses and magnetic moments sum rules No-go theorems Quantum Mechanics: Berry phases
V-A theory of Weak interactions	Electro-weak unification-Standard model
Tachyons	Tunneling (faster than light), Science fiction
Quantum Mechanics: Foundations	Time operator, Uncertainty relations, CPT theorem
Scattering Theory	Cascade model, Re-arrangement collision processes
Open Quantum Systems	Decoherence, Dissipation, Quantum information
Quantum Optics	Diagonal Coherent Representation, antibunching, sub-Poisson statistics, squeezed states, Quantum teleportation
Spin and Statistics	Non-relativistic proof, Extension to higher dimensions, Color symmetry
Quantum Zeno Effect	Quantum control, Quantum Technologies
Tomography	Computerized Industrial Tomographic Analyzer System (CITA) Physics Applications

2.10 Scattering Theory

I was fortunate to collaborate with Sudarshan in a few of these investigations [34–36]. We developed the Cascade model [37] to study the multi step decay processes. We used the Friedrich–Lee model. Sudarshan was not very satisfied with the conventional scattering theory using asymptotic states. He preferred using solvable models to analyze those aspects of scattering and decay processes where they were applicable. The Cascade model was then extended to deal with re-arrangement collision processes.

3 Philosophy and Legacy

Sudarshan’s approach to Philosophy was in the same spirit as his approach to Science. It was, not to take anything for granted but to go to the crux of the problem and then follow the logical consequences, to the utter end (like “following a sinking star”) without being distracted by any extraneous considerations. He believed in investigating thoroughly the consequences of the set of precepts on which the system is based. Often he found parallels between physical and philosophical concepts. But he was always careful not to equate the two or assert that one proved the other. Sudarshan was open minded and willing to investigate anything that interested him or piqued his curiosity.

The legacy of George Sudarshan is:

- (1) Being open minded in the pursuit of knowledge.
- (2) Investigating thoroughly the relevant fundamental principles without any external bias and follow through the consequences to their logical end.

(3) Pursuing one’s vocation irrespective of any material rewards; the pursuit and the knowledge gained are in themselves the rewards.

4 Conclusion

Finally no description about George Sudarshan’s contribution will be complete without a quotation or recitation of a Sanskrit verse. Given below is his favorite verse from the Sri Dakshinamurthy Stotram. This verse exemplifies in a sense the complete circle of his quest. If in physics his quest may be described as “from Being to Becoming” the circle was completed in his philosophical quest “from Becoming to Being”.

viśvaṃ darpaṇadr̥śyamānanagarīṭulyaṃ nijāntargataṃ
paśyannātmani māyayā bahirivodbhūtaṃ yathā nidrayā.
yaḥ sāḁśātkurute prabodhasamaye svātmānamevādvayaṃ
tasmai śrīgurumūrtaye nama idaṃ śrīdakṣiṇāmūrtaye

The meaning of the Sanskrit verse is:

Similar to the image of a town as seen in the mirror, When one sees the image of the world within him, The world appears as if it is outside. It is similar to his seeing due to illusion During the state of sleep. That the one real fact appears as many different truths, And he realizes, when he wakes up and sees the reality, That he is really the one and only one Atman, Salutation to the God facing the south, Who is the greatest teacher.

5 Anecdote

Sudarshan's first version of "Particles traveling Faster than Light" with his co-author V. K. Deshpande was sent to *Physical Review* for publication in 1958. There were three referees; the first one said it was incorrect, the second one said it was correct but well known; when Sudarshan requested a third referee, the third one said he had read the manuscript and he agreed with both the referees! Later he rewrote the manuscript with one more author O. M. P. Bilaniuk and got it published in the *American Journal of Physics* [19].

Acknowledgements

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Figure 1: Sudarshan's family. Standing (left to right): George Sudarshan, E. C. Joseph (brother), Thomas Alexander (brother). Sitting (left to right): Ipe Chandy (father), Rajamma (niece), Achamma (mother), Thankamma (sister in law).

Figure 2: Sudarshan's home.

Figure 3: Sudarshan's family and friends.

"THE CABINET"
ST. THOMAS'S HALL
1950-51.

SEATED:- L. to R:- P. G. John, (Minister for Non Veg), K. S. S. Sarma (Speaker), Dr. M. A. Thangaraj, (President), S. Suryanarayanan, (Prime Minister),
P. Ranjitha (Minister for Veg. Mess).
STANDING: L. to R:- B. Muthunayagam (Minister for Entertainments), V. G. Kedlaya (Minister for Debates), A. S. C. Pandian (Minister for Out Door Games),
U. Ramchander (Minister for In Door Games), E. C. George (Minister for Information).

Figure 4: Madras Christian College Batch 1950–1951.

Figure 5: Sudarshan's photograph in Ph.D. Application.

Figure 6: George playing Croquet in Rochester.

Figure 7: *George Sudarshan and Thomas F. Jordan in Rochester.*

Figure 8: Susumu Okubo and George Sudarshan in Rochester.

Figure 9: George Sudarshan lecturing at the Austin Conference in 1971.

Figure 10: *Honorary Doctorate of the Delhi University in 1974.*

Figure 11: The World Academy of Sciences (TWAS) Prize in 1985.

Figure 12: TWAS Award Lecture in 1985.

Figure 13: *With Narasimha Rao (Former Prime Minister of India) and U. R. Rao in Washington DC.*

Figure 14: George Sudarshan and Ilya Prigogine, Les Treilles.

Figure 15: G. Bhamathi, Claude Cohen-Tannoudji, George Sudarshan and Daniel J. Heinzen.

Figure 16: Claude Cohen-Tannoudji and George Sudarshan.

Figure 17: George Sudarshan and Francesco Zaccaria.

Figure 18: George Sudarshan and Giuseppe Marmo in Napoli.

Figure 19: With R. E. Marshak at the 60th Birthday symposium held at Austin in 1991.

Figure 20: With S. L. Glashow and G. Bhamathi at the 60th Birthday symposium held at Austin in 1991.

Figure 21: George Sudarshan and Steven Weinberg discussing complete positivity in Weinberg's office at Austin.

Figure 22: George Sudarshan and Steven Weinberg at Austin.

Figure 23: *With the Vice Chancellor of Santiniketan and G. Bhamathi receiving the Desikottama award in 1998.*

Figure 24: With the former President of India, Dr. A. P. J. Abdul Kalam and G. Bhamathi in 2005.

Figure 25: Sudarshan receiving the Padma Vibhushan Award in 2007 from the then President of India, Dr. A. P. J. Kalam.

Figure 26: Dirac Medal awarded in 2010.

Figure 27: George Sudarshan and G. Bhamathi in front of UT Tower lit in honor of Dirac Medal.

Figure 28: With Białynicki Birula and Zofia Birula in Warsaw 2017.