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TRIBUTE

A tribute to Sir Jagadish Chandra Bose (1858–1937)

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Abstract First, we provide a brief description of the life of Sir Jagadish Chandra Bose (1858–1937), his contemporaries, and some of his achievements. He is known for demonstrating the World's first wireless communication link at a wavelength of 5 mm. Then, we describe his contribution to photosynthesis research, as published in one of the earliest books on photosynthesis—a 1924 book entitled "*Physiology of Photosynthesis.*" His pioneering work on photosynthesis preceded much of the future work in this area. In particular, we emphasize his work on *Hydrilla* that was a precursor to C-4 photosynthesis.

Keywords J. C. Bose · Lady Abala Bose · S. N. Bose · C-4 photosynthesis · Crescograph · *Hydrilla* · M.G. Marconi · Photosynthesis · Physiology of photosynthesis · Lord W. S. Rayleigh · Meghnad Saha · Rabindranath Tagore

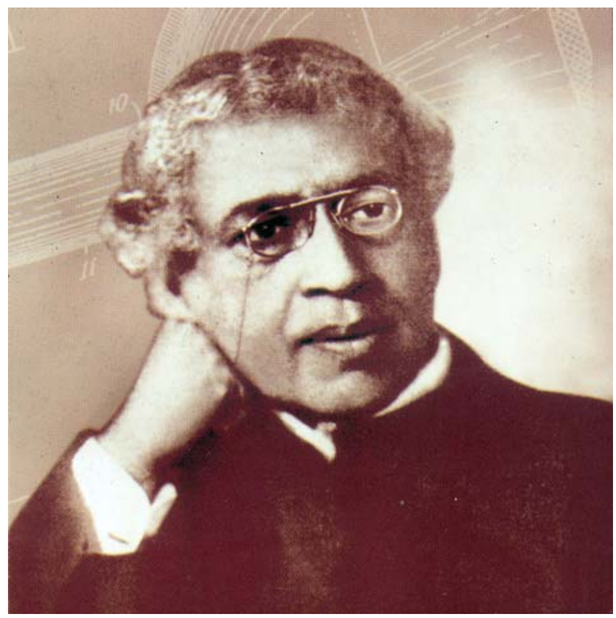

Fig. 1 A photograph of Sir Jagadish Chandra Bose. *Source*: Cover page of the souvenir of International Symposium "Acharya J. C. Bose: The Scientific Legacy," Bose Institute, Kolkata, 2004

Early life

Sir Jagadish Chandra (also spelled as: Jagadis Chunder) Bose was a pioneer who made landmark discoveries in several fields (Fig. 1). He was born on November 30, 1858, in the town of Mymensingh (now in Bangladesh) in an educated and cultured family. His father, Bhagaban Chandra Bose, worked initially as a Headmaster in a school in Maymensingh and later as a Deputy Magistrate in the district of Faridpur (now in Bangladesh). His mother, Bamasundari Devi was a lady of strong personality. The life of Jagadish Chandra was greatly influenced by the struggles in the careers of his parents.

Bose had his early education in a Bengali medium school at Faridpur and, in 1869, he moved to Calcutta (now Kolkata) where he learned English. At first he was admitted to Hare School, but after 3 months he

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was transferred to St. Xaviers School. After passing the Entrance Examination from this School in 1875, he was admitted to St. Xaviers College, Calcutta, and passed the FA (First Art) and BA Examinations in 1877 and 1880, respectively. He read Latin as one of his subjects during this period. Then he went to England in 1880 for higher education. At first he was interested in studying *medicine*, but due to ill health he had to abandon this subject. He then joined Christ College, Cambridge in January 1881, and in 1884, Bose was awarded the BA degree of Cambridge University, passing the *tripos* in Natural Sciences. A little later in the same year, he received a B.Sc. degree from the London University.

World's first wireless communication link

J.C. Bose was a pioneer in research on ''millimeter waves'' in physics. His apparatus included the following components (A.K. Sen 1997): (1) A spark transmitter generating a sharp polarized beam of millimeter waves; (2) A sensitive ''coherer'' and metal contact detector for millimeter waves; (3) A galena detector; (4) Horn antenna; (5) Dielectric lens; (6) Wire grid polarizer; and (7) Curved diffraction grating at millimeter waves.

Using these components, Bose developed experimental setups for: (A) Wireless radio remote control with millimeter waves; (B) Measurement of refractive indices of dielectric materials; (C) Measurement of wavelength of a millimeter waves, using millimeter waves grating; and (D) Measurement of polarization of millimeter waves, using a wire grid polarizer.

J.C. Bose developed the World's first wireless communication link at 5-mm wavelength (at 60 Ghz), using a spark transmitter and a spiral '*coherer*' as the receiver. *In 1895, the transmitted signal was received through two walls of intervening rooms in the Town Hall in Calcutta and through the body of William Mackenzie, the Lieutenant Governor of Bengal, that led to his firing a gun.* This was before the success of Marconi (1874–1937; Nobel Prize in 1909)[1] in wireless communication at longer wavelengths (A.K. Sen 1997). Later, Bose repeated his experiment at one of the meetings of the British Association of Advancement of Science, Liverpool, in front of a distinguished audience, which included Lord Kelvin (1824–1907; born as William Thompson).

This seminal work of Bose created not only a new science of microwaves, but also a new science of radio communication (Mitra 1997).

Professor of Physics at Presidency College, his academic career and other activities

On his return from England in 1884, he joined the Presidency College, Calcutta as a Professor of Physics, which was possible only because of the intervention of Lord Ripon, the then Viceroy of India. Bose was given a lower salary than his European counterparts serving in the same position, since he was an Indian. Being inspired by the Indian national spirit, he did not accept any salary for 3 years; this was the way he protested this unfair practice. Ultimately, good sense prevailed among the authorities and due honor was given to him by payment of the same salary given to the Europeans.

Marriage

Jagadish Chandra was married to Lady Abala Bose (nee Das) (1865–1951)[2] (Fig. 2) on January, 1887. An educated lady, Abala hailed from a good family with a strong cultural background. She used to accompany her husband in almost all his foreign tours associated with scientific activities; she took care of him and provided inspiration to him during these trips.

Research

After joining Presidency College, Bose faced financial hardships. However this did not prevent him from setting up his laboratory in the Presidency College for initiating and carrying out novel and outstanding

[1] *Marchese Guglielmo Marconi* (April 25, 1874–July 20, 1937). Marconi, a contemporary of J.C. Bose, who was recognized for his wireless telegraphy and Radio, was born in Bologna, Italy. He studied Physics and became interested in the work of Hertz on the electromagnetic wave and in generating radio waves. In 1895, he was able to first send signals through a distance of 1 mile and then across 9 miles. In 1909, he was awarded a Noble Prize, jointly with Carl Ferdinand Braun ''*in recognition of their contribution to the development of wireless telegraphy.*'' (Source: Asimov 1971; see Biography No. 838)

[2] *Lady Abala Bose* (August 8, 1865–April 25, 1951). Abala Bose (nee Das) was born in Barisal (now in Bangladesh). She spent her childhood there with her father Durgamohan Das and mother Brhammamayee. In 1871, Durgamohan settled in Calcutta (now Kolkata) with his family and educated his children there. Abala received the First Art (FA) in 1883. Then she completed a course in Medicine (1885–1886) at the Madras Medical College but could not appear for the Examination. She was married to Jagadish Chandra on February 27, 1887. Abala communicated the success of J.C. Bose through her letters to Rabindranath Tagore, Bose's closest friend, and the great poet. (Source: Ray and Bhattacharya 1963.)

research work. Jagadish Chandra frequently visited European countries and delivered lectures on topics of his research. He received the D.Sc. degree of London University in 1896 for his work on the determination of wavelength of electric radiation by diffraction grating (Ray and Bhattacharya 1963). The paper by J. C. Bose on this topic was communicated by Lord Rayleigh (1842–1919; Nobel Prize in 1904)[3], Bose's teacher at Cambridge, to the Proceedings of the Royal Society, and was published in 1897 (Bose 1897). His first visit to the USA was in 1908 where he received much respect and honor from the American scientific community.

After retirement from Presidency College, Calcutta, in 1915, he accepted in the same year an honorary position as Emeritus Professor in the Department of Physics in the newly founded University College of Science. In 1917, Bose Research Institute was established after his name. Here, he was able to utilize his scholarly background in Physics to start work on plant physiology with renewed vigor. He performed many skillful experiments to demonstrate that plants had life and responded to stimuli (S.P. Sen 1997).

Contemporaries

During his long academic career, he had inspired quite a good number of young talents: Satyendra Nath (S.N.) Bose (1894–1974)[4] and Meghnad Saha (1893–1956)[5] later became internationally known scientists. Among his contemporaries, we mention the names of (1) Acharya Prafulla Chandra (P.C.) Ray (1861–1944)[6] (2) Sister Nivedita (1867–1911)[7] who came in close contact

[3] *Lord J. W. S. Rayleigh* (November 12, 1842–June 30, 1919). Jon William Strutt Rayleigh, an English physicist, who was one of the teachers of J.C. Bose, was born near Malden, Essex, UK. In 1879, he became the Director of the Cavendish Laboratory at Cambridge. Lord Rayleigh worked out an equation to account for the variation of light scattering with wavelength. He also worked on the blackbody radiation. Rayleigh received the 1904 Noble Prize in Physics. (Source: Asimov 1971, Biography No. 434)

[4] *Satyendra Nath Bose* (January 1, 1894–February 4, 1974). Satyendra Nath Bose was a student of Sir J.C. Bose in his B.Sc. class in Presidency College. He was born in Calcutta (now Kolkata). In 1924, he provided an alternative derivation of Planck's law (Planck (1856–1947; Nobel Prize, 1918) of spectral distribution of black body radiation (S.N. Bose 1924). Being unable to publish this work in the journal ''*Philosophical Magazine*'' he sent the article to Albert Einstein requesting him in the forwarding letter to arrange for its publication in *Zeitschrift für Physik*. Einstein realized the importance of the work and acceded to his request with a note (translated as: ''Bose's method of derivation of Planck's Law, in my opinion, signifies a forward step. The method applied here yields the Quantum theory of ideal gases as I will show elsewhere.''). Einstein published two articles (Einstein 1924, 1925) and thus a historic letter written by S.N. Bose to Albert Einstein led to the foundation of Quantum statistics known as *Bose-Einstein Statistics* or Bose statistics (Singh 1974). Other details are: M.Sc. in Mathematics, University of Calcutta; Lecturer in Physics, University College of Science; Reader in Physics (Dacca University, now in Bangladesh); visited Berlin where he was warmly welcomed by Einstein; Professor and Head of the Department of Physics (Dacca University); Khaira Professor of Physics (Calcutta University); Vice-Chancellor of *Viswabharati*; National Professor of India; and Fellow of the Royal Society of London. S.N. Bose witnessed the entire world celebrating the 50th year of Bose Statistics. Bose has left behind a class of fundamental particles, obeying his statistics, the 'bosons' which will bear his name forever. (Sources: Singh 1974; Bhattacharjee 1974)

[5] *Meghnad Saha* (October 6, 1893–February 16, 1956). Meghnad Saha, a student of J.C. Bose, was born in the village of Sheoratali, near Dacca (now in Bangladesh). In 1920, he had put forward his famous theory of thermal ionization and applied the theory in the field of astronomy, leading to the foundation of modern astrophysics. Other details are: He was from a poor family; earned scholarship to go to College; attended Presidency College, Calcutta; B.Sc. in Mathematics; M.Sc. in Mathematics (Satyendra Nath Bose was one of his classmates here); Lecturer in Physics, University of Calcutta; D.Sc., Calcutta University; Khaira Professor of Physics, and later Palit Professor of Physics at Calcutta University; Professor and Head of Physics Department of Allahabad University; Fellow of the Royal Society (FRS) of London; and founder of the Institute of Nuclear Physics (Calcutta), named later as the Saha Institute of Nuclear Physics. (Source: Basu 1994.)

[6] *Acharya Prafulla Chandra Ray* (August 2, 1861–July 16, 1944). Acharya Prafulla C. Ray (also spelled as Roy), a contemporary of J.C. Bose, was born in the village Raruli in the district of Jassore (now in Bangladesh). In 1902, P. C. Ray wrote a book entitled *''History of Hindu Chemistry,''* which embodied the details of chemical studies in ancient India; he also had a profound interest in the English literature. He was inspired by nationalistic spirit of his time, and was associated with many philanthropic activities; he was awarded the Knighthood of the British Empire in 1919. He founded the Bengal Chemical Pharmaceutical Ltd. in Calcutta in 1901. Other details are: attended Presidency College, Calcutta; D.Sc. in Chemistry from the University of Edinburgh, Scotland; Faculty of the Chemistry Department, Presidency College (here, he was associated with Sir J.C. Bose); and Palit Professor in the Chemistry Department of the University College of Science of the Calcutta University. (Source: Dhar 1972)

[7] *Sister Nivedita* (October 28, 1867–October 13, 1911). Nivedita was born as Margaret Elizabeth Noble in a small town of Dungannon in North Ireland. She became a teacher at the age of 17. She met Swami Vivekananda in 1895; Margaret left North Ireland and reached India on January 28, 1898 to join Vivekananda's task of building India. On March 25, 1898, Margaret Noble was formally initiated with the name Nivedita. She set up a girl's school in Calcutta and started work for women's education. Working under Vivekananda's ideals, she appealed to Indians to forget all the differences of caste, creed, and culture, and come forward united to serve India. She wrote a book on Swami Vivekananda entitled '*The Master as I saw him*', published in 1910. (Source: Swami Prabhananda 2002)

with the inspiring activities of this great scientist; (3) Swami Vivekananda (1863–1902)[8]; (4) Mahatma Gandhi (1869–1948)[9], who was very impressed by his talent; and (5) Rabindranath Tagore (1861–1941)[10]: his friendship with this great poet was exceptional.

Jagadish Chandra visited different Universities and Research Institutes of the Western countries several times and delivered lectures on topics of his research interest. He came in contact with many distinguished personalities such as Lord Jon William Strutt Rayleigh (1842–1919; Nobel Prize in 1904), Professor Sidney H. Vines (1849–1934), Albert Einstein (1879–1955; Nobel Prize in 1921), Hendrik Antoon Lorentz (1853–1928; Nobel Prize in 1902), Lord Kelvin (1824–1907), W. H. Bragg (1862–1942; Nobel Prize in 1915), Arnold Johannes Sommerfield (1868–1951), George Barnard Shaw (1856–1950; Nobel Prize in 1925), Romain Rolland, (1866–1944; Noble Prize in 1915) and other celebrated personalities who appreciated his research and admired his talent and wisdom.

Literary activities

The literary work of Jagadish Chandra is also noteworthy. His creation ''*Abyakta*'' (The Unexpressed), which is regarded by literary critics as a masterly exposition of the beauty of natural phenomena may be cited as an example. The exchange of ideas between the two great personalities, Tagore and Bose, and their mutual literary influence, became instrumental in the creation of a new culture, adopted by the entire nation. In recognition of his literary work, he was made the president of the Bangiya Sahitya Parishad (the apex body of the State-level literary council for the Bengali language and literature). What all these savants appreciated most was Bose's attempt to prove the age-old humanist faith in the basic unity of all life. A British editor once wrote: ''In Sir Jagadish the culture of 30 centuries has blossomed into a scientific brain of an order which we cannot duplicate in the West.''

Bose's instruments

During his long research career, J. C. Bose fabricated many novel instruments and apparatus to meet the specific needs of his experiments: Oscillating recorder, recorder for the ascent of sap, photosynthetic recorder (that automatically inscribed on a moving drum the rate of carbon assimilation by plants; it was extremely sensitive since it detected the formation of carbohydrate as a millionth of a gram per minute), *crescograph* (that was an instrument for measuring growth of a plant, recording it even at 1/100,000 inch per second), magnetic crescograph (that recorded movements beyond the highest powers of microscope, the magnification produced being 50 million times), *transpirograph* (that determined the quantity of water transpired by a single stoma of the leaf), magnetic radiometer (that made accurate measurement of energy of every ray in the solar spectrum), resonant recorder (that inscribed time as short as a 1/1000 part of a second, and allowed the most accurate determination of the latent period of the plant, and the velocity of transmission of excitation), and a conductivity balance (that determined the

[8] *Swami Vivekananda* (January 12, 1863–July 4, 1902). Swami Vivekananda was born as Narendranath Datta in Calcutta. He was educated in Scottish Church College, Calcutta. In his search for a religious master, he found Paramhansa Ramakrishna and became his disciple. Vivekananda joined the World's parliament of religions held in Chicago in 1893 as a representative of Hinduism. His historic speech was so captivating that a newspaper described him as ''*an orator by divine right and undoubtedly the greatest figure at the parliament.*'' In 1897, Vivekananda founded the Ramkrishna mission at Belur Math, near Calcutta, on the river Ganges in 1897. (Source: Encyclopaedia Britannica 2006).

[9] *Mahatma Gandhi* (October 2, 1869–January 30, 1948). Mahatma Gandhi, also a contemporary of J.C. Bose, was born as Mohandas Karamchand Gandhi at Porbandar, Gujarat, India. He studied at Samaldas College in Bhavnagar, Gujarat and sailed for England in September 1888 and joined the *Inner Temple* in London, UK, becoming a Barrister-at-law in 1891. After his work in South Africa, Gandhi returned to India. He started the '*Quit India*' movement in 1942, demanding on immediate British withdrawal from the country. India finally received its Independence on August 15, 1947. For his devotion to truth and doctrine of '*Satyagraha*' (meaning nonviolent protest), he was respected and admired by other contemporaries of J.C. Bose (Rabindranath Tagore, Albert Einstein, and Romain Rolland) besides millions of people throughout the entire world. He was an ardent leader of three major revolutions of the 20th century: against colonialism, racism, and violence. Gandhi is more popularly admired as 'Mahatma' (Great soul) throughout the world and is recognized as the Father of his Nation, India. (Source: Encyclopaedia Brittanica 2006)

[10] *Rabindranath Tagore* (May 7, 1861–August 7, 1941). Rabindranath Tagore, with whom J.C. Bose was associated, was born in Calcutta. He was educated at his home. He was a poet, short story writer, composer of songs, artist, essayist, and novelist among many other aspects of art and culture. In 1901, Rabindranath founded a school in Santiniketan (Abode of peace) in the district of Birbhum, West Bengal, where he sought to blend the best of Indian and Western traditions. The school became a University, the Visva Bharati in 1921. The book ''Gitanjali'' (song offerings), containing Tagore's English translations of poems from several of his Bengali verse collections, was hailed by W.B. Yeats (1865–1939); Noble Prize in literature in 1923. Tagore was awarded the Nobel Prize in literature in 1913, and the Knighthood in 1915; he repudiated the knighthood in 1919 as a protest against the British atrocities in Amritsar. Two of his songs—''*Jana Gana Mana*'' and ''*Amar Sonar Bangla*'' have been adopted as the national anthems of India and Bangladesh, respectively. (Source: Kapila and Kapila 2002)

Fig. 2 A photograph of Lady Abala Bose. *Source*: Nari Siksha Samiti Sansad (2004), Kolkata

effect of various drugs on enhancement or depression of the electrical impulse). A sketch of Bose's compound lever crescograph, which records plant growth automatically and of his Photosynthetic Recorder, by which the rate of photosynthetic activity is automatically recorded, is shown in Figs. 3 and 4, respectively.

Bose's books

Jagadish Chandra published his findings in the form of books probably because he had difficulties in getting his papers published in the British Journals. (There are several speculations on this topic.) These books (also see Fig. 5 (Right)) were entitled: *Response in the Living and Nonliving* (Bose 1902); *Plant Response as a means of Physiological Investigation* (Bose 1906); *Comparative Electrophysiology* (Bose 1907); *Researches on the Irritability of Plants* (Bose 1913); *Physiology of the Ascent of Sap* (Bose 1923); *Physiology of Photosynthesis* (J.C. Bose 1924); *Nervous Mechanism of Plants* (Bose 1926); *Plant Autographs and their Revelations* (Bose 1927); *Motor Mechanism of Plants* (Bose 1928a); and *Growth and Tropic Movements of Plants* (Bose 1928b).

Honors

Bose was honored with a Knighthood by the British Government in 1916. As recognition of his pioneering research work in Physics and Physiology, Jagadish Chandra was elected as a Fellow of the Royal Society of London in 1920. He is still respected throughout India as '*Acharya*', meaning the most revered teacher. The life and achievements of this great scientist have been described in depth by Manoj Ray and Gopal Chandra Bhattacharya (Ray and Bhattacharya 1963).

J.C.Bose passed away amidst glory in 1937 at Giridih in Bihar, India.

Photosynthesis

During his research life, Bose carried out some very important experiments on photosynthesis, particularly on its physiological aspects. Speaking in the simplest terms, photosynthesis in plants may be described as the process by which CO_2 and H_2O are converted to glucose moiety and oxygen. The process involves a large number of steps catalyzed by enzymes (Rabinowitch and Govindjee 1969; Blankenship 2002). A brief description of Bose's work is provided below.

Bose presented the results of his studies on photosynthesis, in the form of a book, '*The Physiology of Photosynthesis*' published in 1924 by Longman, Green and Co. (J.C. Bose 1924). The title page of the book is

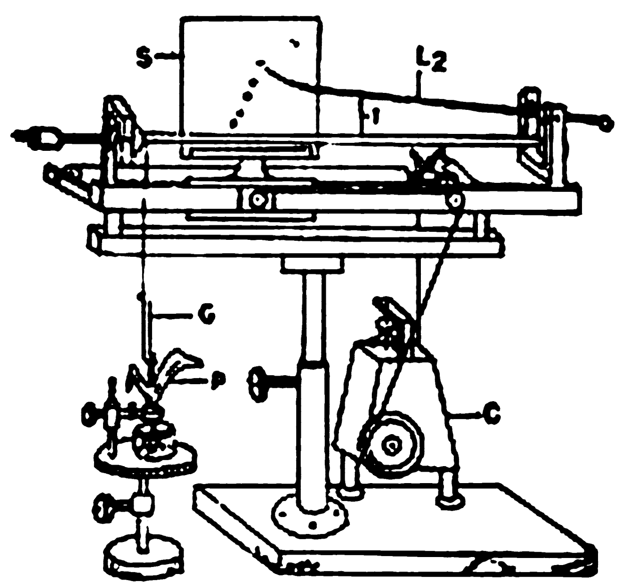

Fig. 3 A sketch of a compound lever crescograph of J.C.Bose. *Source*: S.P. Sen (1997). The symbols C, G, L_1, L_2, P, and S in the figure represent clock, governor, lever 1, lever 2, plant, and screen, respectively

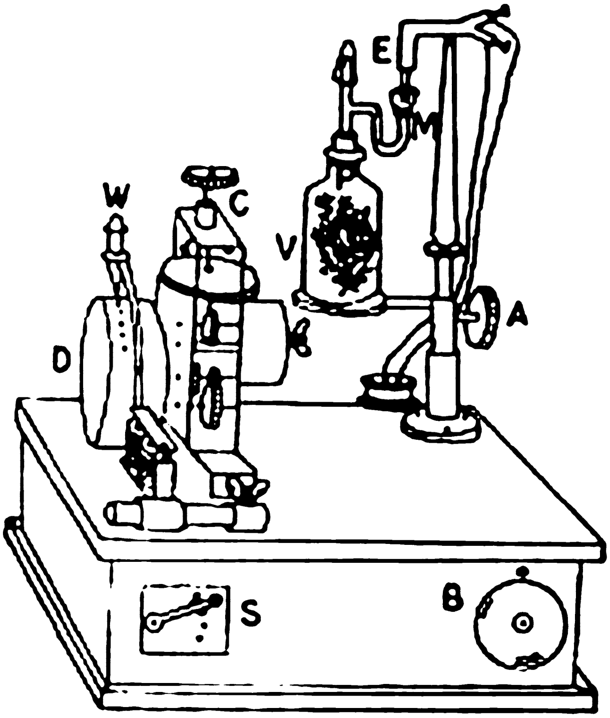

Fig. 4 A sketch of a photosynthetic recorder of J.C. Bose. *Source*: S.P. Sen (1997). The symbols A, B, C , D, E, M, S, V, and W in the figure represent adjustable screw, bell, clock, drum, electrical arrangement, mercury switch, switch, glass vessel, and writing pen, respectively

shown in Fig. 5 (left); Fig. 5 (right) shows a list of his books and one, published in 1920, by Patrick Geddes on Bose himself. In view of the fact that the 1924 book is not easily available at present, we have provided below the content of the book. The book has 28 chapters and 286 pages. The titles of the chapters of this book are: (1) Introduction; (2) The evolution of pure oxygen under light; (3) Determination of rate of evolution of equal volumes of oxygen; (4) The automatic record of the rate of evolution of oxygen; (5) Photosynthesis under increasing intensity of light; (6) Relation between the quantity of light and the amount of photosynthesis; (7) The physiological factor in photosynthesis; (8) Change in photosynthetic activity under stimulus: Anesthetics and poisons; (9) Effect of infinitesimal traces of chemical substances on photosynthesis; (10) The electric response to light; (11) Phenomenon of photosynthetic induction; (12) Effect of intermittent light on photosynthesis; (13) The automatic radiograph; (14) The electric photometer; (15) Relation between CO_2 supply and photosynthesis; (16) Photosynthetic evolution of oxygen in the complete absence of carbon dioxide; (17) Effect of variation of temperature on photosynthesis; (18) The tonic factor on photosynthesis; (19) The daily variation in photosynthetic activity; (20) Determination of the

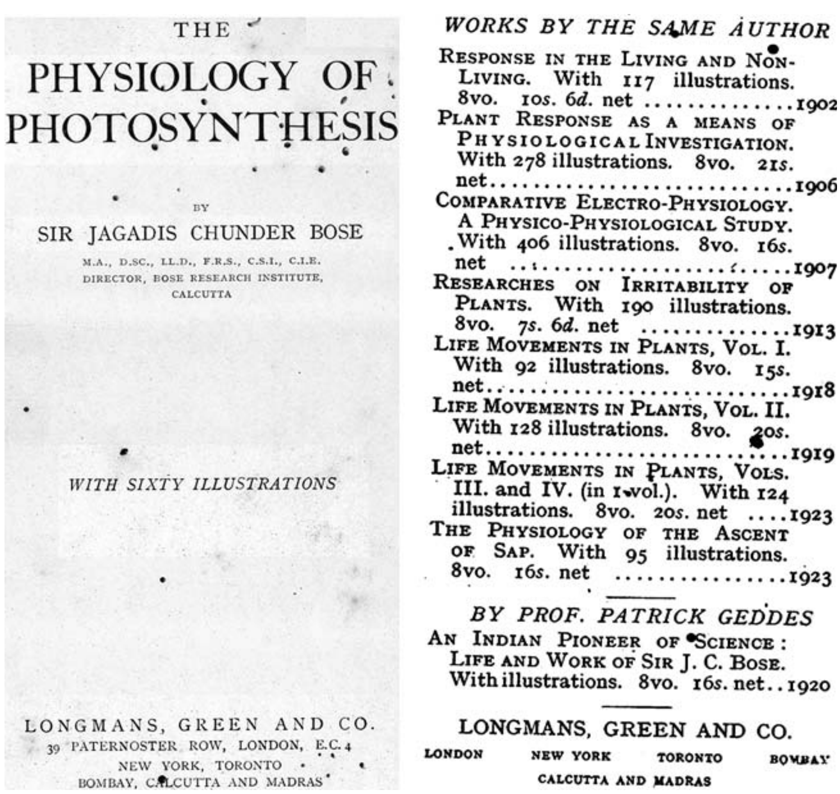
THE
PHYSIOLOGY OF
PHOTOSYNTHESIS

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Fig. 5 (Left) A photograph of the title page of the book entitled "Physiology of Photosynthesis" written by Sir J.C. Bose in 1924; (Right): A list of his books as well as a 1920 book on him (from the 1924 book) photosynthetic efficiency of light of different colors; (21) Determination of the energy of the different rays in the solar spectrum; (22) Determination of photosynthetic efficiency of spectral rays; (23) Determination of the increase of weight due to photosynthesis; (24) Simultaneous determination of carbohydrate formation by two independent methods; (25) Efficiency of the photosynthetic organ in storage of solar energy; (26) The physiological scale and the law of photosynthesis for the different factors; (27) Photosynthesis under simultaneous variation of different factors; and (28) General review. The contents show the versatility of the topics covered already in 1924; they reveal the breadth and the depth of J.C. Bose's interests and interpretations in the area of photosynthesis.

Use of aquatic plant Hydrilla

Salil Bose (Bose 1982) has highlighted Sir J.C. Bose's extensive studies of the photosynthetic characteristics of *Hydrilla* in summer and winter seasons. (See the next section and Agepati S. Raghavendra, P.V. (Raj) Sane and Prasanna Mohanty (pp. 1189–1204) in Govindjee et al. (2005) for photosynthesis research in India.) J. C. Bose had selected an aquatic plant *Hydrilla*, and used it extensively for his photosynthesis research. He ascribed the following main reasons for selecting the plant (J.C. Bose 1924, p. 4): (1) The plant may be maintained under normal conditions in a vessel of water; (2) There is no transpiration to modify the normal activity; (3) The absence of complicating stomata; and (4) The facility of escape of the excreted oxygen from the intercellular species.

Photosynthesis experiments of J.C. Bose (1924)

It is quite astonishing that in the early 1920s when standard instruments were not available for quantitative measurements, Bose ventured to devise many indigenous instruments to record many useful, precise, and quantitative data. Some of the important results derived from these data are as follows:

- A strong electric shock caused an arrest of photosynthesis, the period of arrest being prolonged with increased intensity of stimulus.
- In studying the effect of light, Bose (1924, p. 48) observed that the CO_2 assimilation by the green leaf of *Hydrilla* is an anabolic process; this plant is very sensitive to light and so it may be used as a photometer. Bose observed that with increased duration of exposure and the intensity of light, photosynthesis increased, or in other words, the amount of photosynthesis was proportional to the quantity of the incident light.
- In studying the relative efficiencies of different *rays* of light, Bose (1924, p. 168) employed the method of flotation in which a piece of *Hydrilla* was suspended from the pan of a torsion balance. A magnetic radiometer which recorded an increase of ~10^{-5} degree Celsius was also used, so that simultaneous determination of photosynthetic activity and the energy of the different *rays* were made possible. The relation between photosynthesis and the energy of the incident radiation was established by the simultaneous determination of the activity by the *bubbler* and of the intensity of radiation by the radiometer. Photosynthesis, though weak, was found to rise gradually. One of the absorption maxima Bose (1924, p.194) noted was at 680 nm, which was attributed to the absorption of this particular wavelength of light by chlorophyll. The characteristic effects in different spectral regions were explained to be due to different energy of the *rays* and their relative absorption and also to the complimentary reactions in the induction of photosynthesis and phototropism.
- Bose (1924, Chapter XV) investigated the relation between CO_2 supply and photosynthesis. He provided evidence for the fact that no photosynthesis, in normal condition, can occur in the absence of CO_2 whereas excess CO_2 produces a narcotic or poisonous effect. (The photosynthetic curve under different CO_2 concentrations is given in Fig. 6 reproduced from Fig. 33 in Bose (1924, p. 115).) The general characteristics exhibited by the curve regarding CO_2 supply pointed out that the curve was linear up to a concentration of about 8 mg of CO_2 per 100 ml. After this, it gradually approached the maximum. The coefficient for CO_2 concentration was defined as

$$K = \frac{\lambda_c - \lambda_{c'}}{c - c'} \quad (1),$$

where λ_c and $\lambda_{c'}$ are the activities for the respective higher and lower concentrations c and c'. The coefficient is the measure of the efficiency of CO_2 utilization. The value of the average coefficient in winter was determined to be 39.9 whereas in spring, the coefficient was nearly doubled (Bose 1924, p. 120).
- *Precursor to the C-4 pathway*. Bose found that *Hydrilla* plants at high temperatures became acid. Photosynthesis, measured by evolution of oxygen, was, apparently, also found to occur in the complete absence of carbon dioxide in this plant. Bose also

studied the assimilation of organic acids by substituting malic acid for carbon dioxide. Photosynthetic curve under increasing concentration of CO_2 and of malic acid solution is given in Fig. 7 (reproduced from Fig. 36 in Bose (1924, p. 129)). Bose demonstrated that organic acids present in the plant were assimilated instead of CO_2; the absorption of CO_2 by these plants is less than normal. He concluded that the assimilatory quotient, given by the ratio of the quantity of oxygen to CO_2 in acid plants was greater than unity whereas the respiratory quotient CO_2/O_2 was less. *It is quite astonishing that as early as 1924, J. C. Bose visualized the idea, which with later advancement in biochemical research on the subject might be thought to be as a precursor to the concept of photosynthetic pathway of C-4 characteristics* (see Hatch (pp. 875–880) in Govindjee et al. 2005). Earlier to C-4 pathway of CO_2 fixation, C-3 pathway was established by Melvin Calvin, Andrew Benson, James Al Bassham, and their co-workers (Bassham and Calvin 1957). A fundamental account of the path of carbon in photosynthesis has been provided by Rabinowitch and Govindjee (1969); for historical accounts, see Benson (pp. 793–813) and J.A. Bassham (pp. 815–832) in Govindjee et al. (2005).

- Bose considered the determination of photosynthetic activity from different sources of light for the sake of accuracy in some cases of his measurements. He also studied the photosynthetic curve at different temperatures by using a device that provided a gradual rise in temperature. The photosynthetic activity in *Hydrilla* was found to increase uniformly in the temperature range from 17°C to 28°C, beyond which an abrupt decline was noticed. The temperature coefficient, K, was determined by the use of the formula

$$K = \frac{A_T - A_t}{T - t} \quad (2),$$

where, A_T is the activity in cubic mm per hour at T and A_t is that at t ($T > t$). Experimentally, the value of the coefficient was found to be 20.4. It was found that a 7°C rise of temperature caused the increase of the photosynthetic activity by 2 times, whereas a 10°C rise increased it by 2.2 times.

- In studying the effect of *tonocity* (pressure) on the photosynthesis, Bose was able to formulate the law of photosynthesis as: the ratio of activity to tonocity is a constant. The constancy was also observed for variation of the photosynthetic activity with temperature, CO_2 concentration and light.

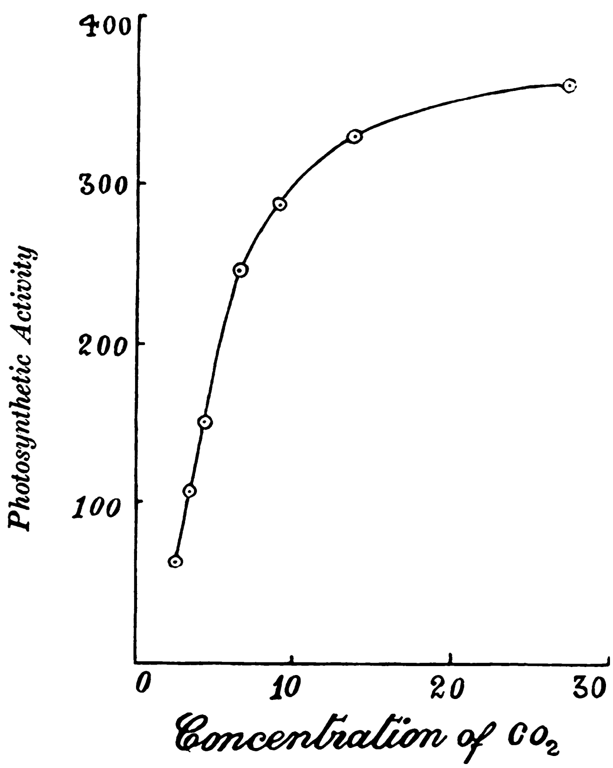

Fig. 6 Photosynthetic curve: Photosynthetic activity (arbitrary units) as a function of CO_2 concentration (milligram/100 cubic cm). Photosynthesis was measured by the activity in cubic millimeter of oxygen/per hour. *Source*: Fig. 33 in J.C. Bose (1924)

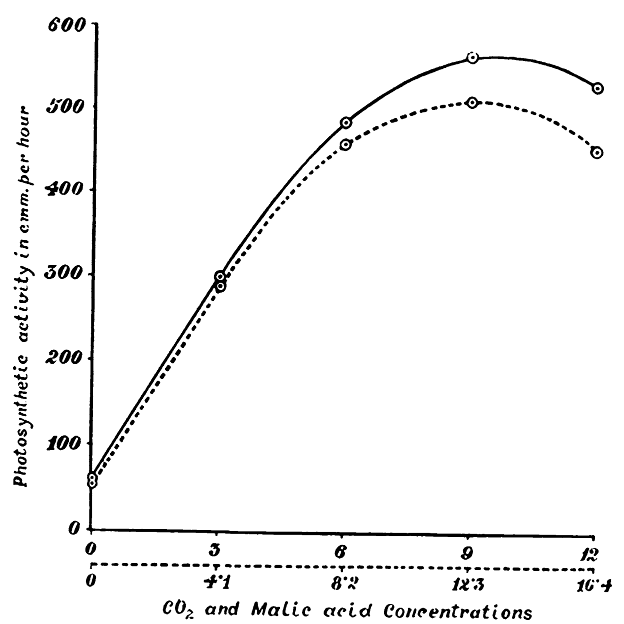

Fig. 7 Photosynthetic curves under increasing concentration of CO_2 (upper curve) and malic acid solution (lower curve): Photosynthesis activity (in cubic millimeter/hour of oxygen evolved). The upper abscissa represents CO_2 concentration in milligram/100 cubic cm and the lower dotted one represents *n* parts of malic acid in 10,000 parts of water. *Source*: Fig. 36 in J.C. Bose (1924)

Fig. 8 A 2003 photograph of the authors, Dibakar Sen (left) and Dulal Mukherjee (center), with the editor Govindjee (right). Photograph by Rajni Govindjee

- J. C. Bose undertook an extensive series of investigations on photosynthesis under simultaneous variation of different factors, namely CO_2 concentration, light, temperature, and '*tonocity*'. He made separate experiments taking two variable factors, three variable factors, and even four variable factors of the above mentioned quantities and was able to generalize the photosynthetic law by stating that when there is a simultaneous variation of different factors in photosynthesis, each factor contributes its full independent effect and the resultant effect is not the sum but the product of the effects of the individual factors. This is the law of product, which he expressed by the general formula

$$A/C\ L\ P\ T \text{ is a constant,}$$

where, the symbols A, C, L, P, and T denote photosynthetic activity, carbon dioxide concentration, light intensity, pressure, and temperature, respectively.

The comparative results and discussion of J. C. Bose's investigation with *Hydrilla* in summer and winter seasons are available in the paper of Salil Bose (1982).

Work during pre-Bose era (Heyne 1815) and later work on the subject by several others (Basu and Sen 1959; Stanley and Naylor 1972; Bowes et al. 1978) on the same topic has been discussed by Salil Bose (1982). In J. C. Bose's time, biochemical interpretations were not available. Subsequent work provided such explanations with the development of the subject to the present stage (Leegood et al. 2000).

Conclusions

Sir J. C. Bose's work on photosynthesis with *Hydrilla* is a landmark in photosynthetic research. His observations have led to many important conclusions, and had initiated much research on photosynthesis. The biological significance of seasonal adaptation and the mechanism of CO_2 fixation have become the subject matter of modern research. Sir J. C. Bose may rightly be considered as an early pioneer in research in the field of photosynthesis. His thought and vision has illuminated the path of research in the field since 1924.

We end this tribute to Sir Jagadish Chandra Bose with a picture of two of us (DCM and DS) with the Editor Govindjee at the time he invited us to write this article (Fig. 8).

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