CHANDRASEKHARA VENKATA RAMAN

Raman, in a portrait painted in the 1950s.

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India's 'great savant' of science made deep contributions to acoustics, physical optics, magnetism, molecular physics and especially to our understanding of the scattering of light by matter.

Aiyasami Jayaraman and Anant Krishna Ramdas

The year 1988 marks the centennial of the birth of C. V. Raman, the discoverer of the effect that bears his name. During his extraordinarily creative career, which spanned more than six decades, he had a profound impact on the scientific world.[1] He made significant contributions to acoustics, physical optics, magnetism and molecular physics, including, of course, his extensive studies on elastic and inelastic light scattering. Modern India owes him much for her entry into the world of science, and for the strength of her scientific tradition.

Raman was born in a village near Trichinopoly in the province of Tamil Nadu, India, the second of eight children. His family was of modest circumstances and depended on agriculture for its income. Raman's father, Chandrasekhara Iyer, was the first in the family to receive higher education in the Western educational system introduced by the British, referred to in India as "English" education. India had formally come under the British Crown in 1858; the first three Indian universities based on the Western style—Bombay, Madras and Calcutta—came into existence only in 1857. Iyer obtained a bachelor's degree in the physical sciences and taught physics in a college in Trichinopoly. A scholarly person with intellectual ambitions and strong artistic inclinations, Iyer is reported to have played the violin exceedingly well.

Raman's mother, Parvathi Ammal, the daughter of a Sanskrit scholar, was a gentle, tolerant lady, firmly rooted in the home and family life. In 1892, when Raman was four, Iyer moved his family to the city of Vishakapatnam in the province of Andhra Pradesh, where he had accepted a position as a lecturer in mathematics and physics in Mrs. A. V. N. College, a junior college. Raman spent the next ten years of his life in Vishakapatnam, which lies on the east coast of India, facing the Bay of Bengal with its intensely blue waters.

Raman was clearly special; a precocious child, he finished his primary and secondary education early, matriculating at the tender age of 11. After two years in Mrs. A. V. N. College, he entered Presidency College in Madras and, at the age of 15, passed the examination for his BA at the top of his class, winning gold medals in English and physics. It was evident that Raman's superior intellectual capacities singled him out for a bright career. At the turn of the century this meant studying abroad, and his teachers advised him to go to England. Raman was physically frail, however, and the Civil Surgeon of Madras, who examined him, declared him unfit for the rigors of the English climate. Raman therefore continued his studies in Presidency College, and he received his MA in 1907 at the age of 18, again at the top of his class, with record marks and a gold medal. By this point, his interest in physics had been fully aroused; on his own he studied such works as Lord Rayleigh's scientific papers and treatise on sound, and the works of Hermann von Helmholtz.

While in the MA class Raman published a paper in the November 1906 *Philosophical Magazine* (London) on the "unsymmetrical diffraction bands due to a rectangular aperture, observed when light is reflected very obliquely at the face of a prism." He had observed these bands during a routine class experiment in optics. From his very first research publication Raman demonstrated the ability to discover novel phenomena using simple experiments. He followed this paper with a note in the same journal on a new experimental method for measuring surface tension. These papers were communicated by the author himself and contain no acknowledgment of help from anyone. Presidency College was primarily a teaching institution at that time, and had no tradition at all in research. Whatever Raman did was on his own initiative.

It was abundantly clear that Raman was cut out for a scientific career. However, opportunities in India for such a career were then nonexistent, whereas positions in the civil service were prestigious and financially remunerative. In fact, the civil service was then regarded as the most attractive career for the ambitious, the bright and the young. Because training for the Indian Civil Service involved a trip to England, Raman was ruled out for health reasons. Thus he appeared for the competitive examination for selection into the Financial Civil Service in February 1907. His elder brother C. Subrahmanya Iyer was already a member of the service, and this probably influenced Raman's decision. He secured the first place in the qualifying examination and was selected.

Indian Association for Cultivation of Science

Just before he joined the civil service, Raman married Lokasundari. Accompanied by his wife, he arrived in Calcutta in 1907 to join the finance department as an assistant accountant general. He was only $18\frac{1}{2}$ years old. The Ramans rented a house in Scott's Lane, off Bowbazar Street. In the normal course of events Raman would have had a long career in the finance department of the government of India and, given his abilities, would have moved up the ladder in time, to retire as a respectable accountant general. But Raman was obsessed with physics, and an inner urge drove him to seek an opportunity to fulfill this calling. He then made his first major "discovery"—namely, the presence of the Indian Association for the Cultivation of Science at 210 Bowbazar Street, only a few blocks from his home.

The association had been founded in 1876 by Mahendra Lal Sircar, a leading medical practitioner in Calcutta. Sircar had an abiding interest in science and foresaw the great role it was destined to play in India. He wanted to create an association along the lines of the Royal

Aiyasami Jayaraman is a Distinguished Member of the technical staff at AT&T Bell Laboratories in Murray Hill, New Jersey. **Anant Krishna Ramdas** is a professor of physics at Purdue University.

Institution of London, where young aspirants could pursue scientific interests, and he devoted a good part of his life to collecting funds from Indian princes and affluent citizens to achieve his dream. The association's building had several large halls for laboratories and an excellent lecture theater that could accommodate a large audience. Sircar organized popular-level lecture courses in science for students, which he gave himself or persuaded others to give. However, he was unable to fulfill his dream of a research institution. In those days scientific research in India was nonexistent, and the institution decayed over the following 25 years as rooms grew dusty and laboratories sat idle. In desperation Sircar seems to have declared: "I don't know how to account for the apathy of our people towards the cultivation of science. Younger men must come and step into my place and make this a great institution." Prophetically, that wish was later to be fulfilled by Raman. Sircar died in 1904 a rather disappointed man. His son Amrit Lal Sircar succeeded him as the honorary secretary of the association and guided its affairs.

One day soon after his arrival in Calcutta, Raman noticed the association while riding in a streetcar along Bowbazar Street on his way home from work. He immediately alighted and knocked on the doors of the association, full of excitement. Admitted inside by Ashutosh Dey, who later became his most devoted assistant, Raman met Amrit Lal Sircar and asked if he could conduct research at the association during his spare time. The story goes that Sircar embraced Raman, exclaiming that they had been waiting for a person like him for years, and how happy his father would have been to witness the entry of such a person into the association.

Raman set to work with all enthusiasm and soon started publishing research papers. From 1907 to 1917, except for short absences from Calcutta on temporary transfer to Rangoon and Nagpur, Raman spent all his leisure time at the association, working evenings and very late into the night on his experiments. He had all of the association's facilities completely at his disposal, and the devoted and loyal assistance of Dey as well. Raman soon turned the association into a beehive of activity.

All this meant a different story for Lokasundari Raman, a young bride thrust into the hands of a strange young man with a consuming passion for science. She described the routine of her husband to S. Ramascshan, the 1978 Raman Memorial Lecturer, as follows:

> At 5:30 am Raman goes to the association, returns at 9:45 am, bathes, gulps his food in haste, leaves for his office invariably by taxi to be on time for his work. At 5 pm Raman goes directly to the association on his way back from the office and comes home at 9:30 or 10 pm, after spending the evening hours at the laboratories of the association.

Sundays were spent entirely at the association. Lokasundari ungrudgingly supported Raman in his quest for scientific knowledge throughout his life, endearing herself to all who associated themselves with her husband.

During the period 1907–17, Raman was a full-time civil servant holding a high rank, and was respected and admired as a very capable officer. Despite his full work load he managed to pursue research on problems in acoustics and optics, publishing papers such as "Experimental Investigations on the Maintenance of Vibrations," "Note on the Theory of Subsynchronous Maintenance," "Dynamical Theory of the Motion of Bowed Strings" and "The Experimental Study of Huygens' Secondary Waves" in such journals as *Nature*, *Philosophical Magazine*, *Physical Review*, and the *Bulletin of the Indian Association for the Cultivation of Science*. The publications convey an image of an extremely energetic scientist with a well laid-out scientific program. Raman drew on his deep insights into vibrations and wave motion to select worthwhile problems that were tractable with the limited resources available to him. In his formulation of problems, his careful experimentation, his physical and mathematical analyses applied with a sure touch, and his transformations of apparently simple, routine issues into deep and unexpected insights, one sees in this early work the rapid evolution of a world-class physicist.

Raman's scientific contributions in acoustics earned him an international reputation. His devotion and dedication began to attract young students, teachers and professors from all over India; they gathered around him to participate in the scientific excitement. The Raman school of physics came into being.

Studies in Light Scattering

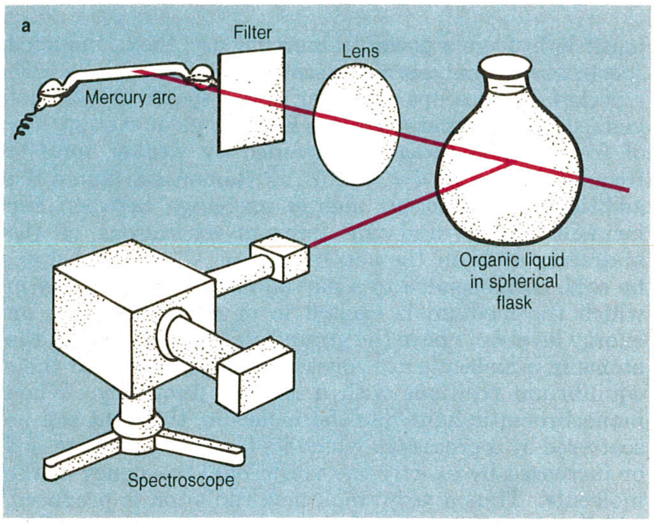
Raman's scientific career changed significantly in 1917. He wrote in 1968: "My studies on bowed string instruments represent a phase of my earliest activities as a man of science. They were mostly carried out between the years 1914 and 1918. My call to the professorship at the Calcutta University in July 1917 and the intensification of my interests in optics inevitably called a halt to my further studies of the violin family instruments."

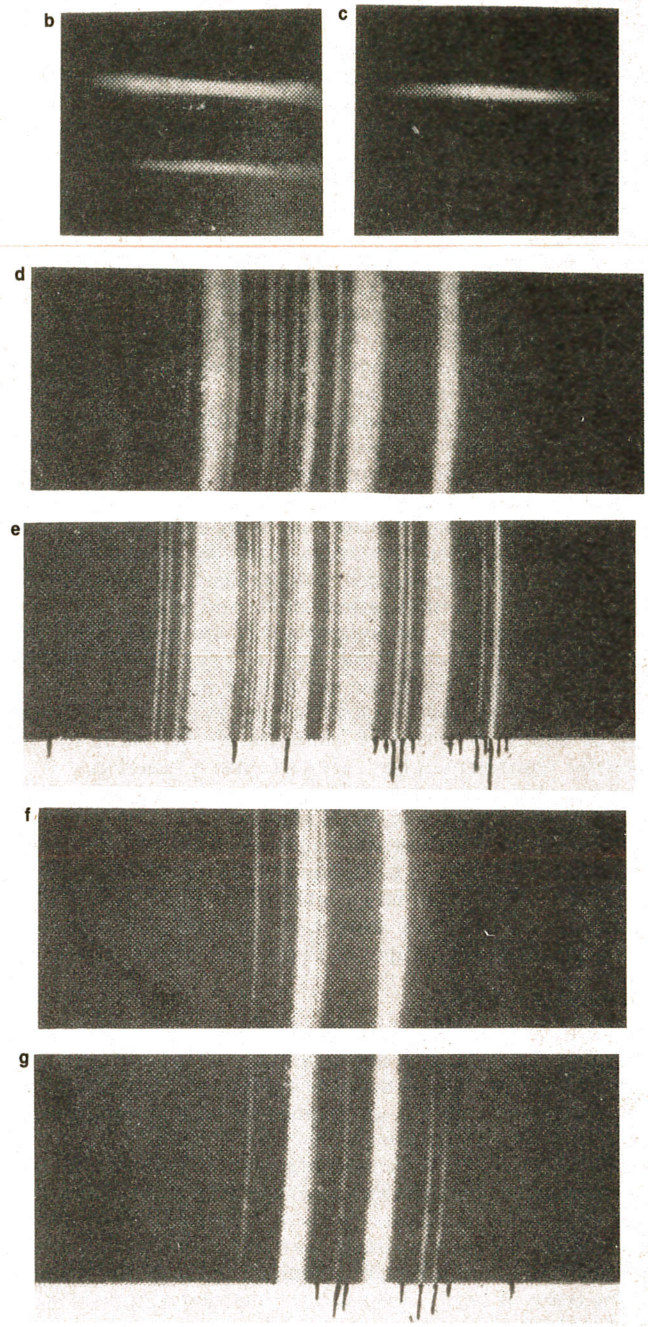
By 1917 Raman had made a profound impression on the leading educators and citizens of Calcutta. Asutosh Mookerjee, the dynamic vice chancellor of Calcutta University at that time, was assiduously engaged in building a first-rate university. He was successful in getting large donations and in attracting eminent scholars and scientists to occupy endowed chairs. He recognized in Raman the ideal person to occupy the Sir Tarakanath Palit Professorship of Physics, which had just been endowed at the University College of Science at Calcutta, and offered it to Raman. However, the appointment required the candidate to have received training abroad. Raman refused to comply with this stipulation, and so the vice chancellor changed the provisions. Finally Raman took the chair and resigned from the civil service, exchanging a lucrative job for one with one-fifth the emolument.

Although he was "under no obligation" to take part in teaching MA and MSc classes according to the "special terms of appointment as the Palit Professor of Physics," Raman took a strong and active interest in modernizing Calcutta's postgraduate curriculum. He fully participated in teaching and inspired his students with his enthusiastic lectures, in which he frequently drew on original papers and classical treatises. M. N. Saha (later famous for the ionization equation named after him) and S. N. Bose (who discovered Bose statistics) were two of the lecturers at the University College in 1917. Raman was led to say, with justifiable pride, "Calcutta University can claim to possess a real school of physics, the like of which certainly does not exist in any other Indian university, and which, even now, will not compare very unfavorably with those existing in the best European and American universities."

In 1921 Raman took his first trip abroad, as a delegate to the Congress of Universities of the British Empire held that year in Oxford. During his brief visit he met the famous physicists of England, including J. J. Thomson, Ernest Rutherford and William H. Bragg. His lecture to the Physical Society on his research in optics and acoustics, which he illustrated with experimental demonstrations, apparently was immensely appreciated by the large body of physicists present.

Many of Raman's scientific investigations were inspired by an intense love of nature and the beauties of nat-





Raman's early spectroscopic studies were carried out with the the apparatus shown schematically in the diagram above (**a**). Light from the mercury arc passed through a filter and a lens before being partially scattered by the sample. The solid line indicates the path of the light. Such an apparatus led to the first Raman spectra (right, see reference 4). The pair of photographs at the top demonstrate the polarization characteristics of scattering in toluene. In **b** a beam of sunlight was filtered through a blue-violet glass, with a double-image prism in front of the camera lens; in **c** the same arrangement was used, except that an additional, complementary green filter was placed in front of the lens. The middle two spectrograms represent the spectrum of the quartz mercury arc lamp in the range 3500–4400 Å (**d**) and the spectrum of radiation in the same range scattered by liquid benzene (**e**). The Raman lines are marked by short black lines. For both spectrograms the light was filtered by blue glass. The bottom two spectrograms (**f, g**) are the same as the middle two, except that the light was filtered by a potassium permanganate solution instead of by blue glass.

ural phenomena. While traveling to and from the Congress of Universities, he was fascinated by the blue of the sky and of the Mediterranean Sea, and his research interests turned toward light scattering. Rayleigh had explained the sky's color as due to the scattering of sunlight by air molecules; he had also conjectured that the blue of the sea was due merely to the reflection of the sky at the water's surface. During his voyage, however, Raman performed a simple experiment, which demonstrated that the color of the sea arises from an intrinsic light scattering by water molecules: He quenched the surface reflection with a Nicol prism at the Brewster angle, and yet the blue of the sea was just as vivid. Convinced by his experiment that the blue of the ocean was a genuine molecular light scattering phenomenon, Raman dashed off several short letters to *Nature* recording his observations. In 1922 he published a comprehensive paper entitled "On the molecular scattering of light in water and the colour of the sea," in the *Proceedings of the Royal Society*.[2]

Raman then focused his entire scientific program on the scattering of light by matter in all states of aggregation. In 1922 he wrote a memoir entitled *The Molecular Diffraction of Light*, in which he described the measurements he had already carried out with his group, and their plans for the future. The latter included studies of the molecular diffraction of light in systems undergoing phase transitions and in liquid mixtures and solutions and research on the relationship of light scattering to chemical constitution. In his book, Raman carefully marshaled the basic physical concepts and discussed important issues such as the Doppler effect in molecular scattering and molecular diffraction and the quantum theory of light, providing impressive insights. One clearly perceives in this memoir a scientist who has seized upon a first-rate research opportunity, who is fully cognizant of the contemporary status of physics and who, having mobilized his intellectual resources, is ready to proceed with energy and enthusiasm. After 1921, investigations on light scattering became the central theme of Raman's program, which culminated in 1928 with the discovery of the Raman effect.

Raman and his students established careful experimental procedures to observe and characterize the very feeble radiations they typically observed. Their meticulous attention to the purity of the scattering medium, their careful exclusion of all spurious and parasitic radiation, and the ready availability in India of intense sunlight over extended periods led to several fundamental discoveries in rapid succession, including:

▷ They verified the Einstein–Smoluchowski theory of fluctuations under diverse conditions, and made a determination of Avogadro's number.

▷ They made a comprehensive study of the departure from complete polarization of transversely scattered light—so-called depolarization—and its relationship to the anisotropy of molecules, as evidenced, for example, by the contrasting configurations of N_2 and CCl_4.

▷ They correlated the anisotropy of molecules with the optical and magnetic anisotropy of crystals, as well as flow, electric and magnetic birefringence.

▷ They interpreted x-ray diffraction in fluids and amorphous solids in terms of concepts closely akin to the Fourier transform of the pair correlation function.

▷ They observed and explained surface scattering, including the striking case of liquid mercury.

▷ They studied light scattering from colloids (the Tyndall effect) and discovered its intimate relationship to osmotic pressure. This paper formulated the technique for determining the molecular weight of colloidal particles, and predates the classic paper of Peter Debye by 17 years.

A new radiation

In 1923, his student K. R. Ramanathan, under Raman's direction, undertook a detailed study of the scattering of light by water and the possible wavelength dependence of depolarization. When an intense beam of sunlight was passed through an optical filter and focused on carefully purified water, the transversely scattered light exhibited a curious anomaly. Contrary to expectations, on examining the scattered radiation with an optical filter whose transmission characteristics were complementary to those of the filter in the incident beam, Ramanathan found a faint trace of light. Suspecting fluorescence due to some residual impurity, they repeatedly and very slowly distilled the water *in vacuo*, but "in spite of many redistillations, the effect remained practically undiminished."[3] Alcohol also exhibited this "persistent feeble fluorescence." The weak fluorescence was repeatedly encountered in several investigations by Raman and his students in the ensuing years. Attempts in 1924–25 to use spectroscopic techniques to analyze this fluorescence were met with failure.

By the end of 1927 Raman felt that the effect was "some kind of optical analogue to the type of x-ray scattering discovered by Prof. Compton."[4] Spurred by this intuition, he and his student K. S. Krishnan established that the effect was exhibited by a large number of liquids, organic vapors and gaseous CO_2 and N_2O, as well as by crystals such as ice and amorphous solids. "Preliminary observations with sunlight filtered through a combination which passes a narrow range of wavelengths, showed the spectrum of the new radiation to consist mainly of a narrow range of wavelengths clearly separated from the incident spectrum by a dark space."[5] Using monochromatic light from a powerful mercury arc, they conducted spectroscopic analyses of the scattered light, initially with a pocket spectroscope and later with a spectrograph, that yielded truly dramatic results. Each incident exciting line of frequency ω_L was accompanied by weaker lines of frequency $\omega_L \pm \omega_i$, $i = 1, 2, 3 \ldots$. Raman attributed the additional lines to an energy exchange between the incident photon and the internal excitations of the scattering medium; the new lines at $\omega_L - \omega_i$ and $\omega_L + \omega_i$, he said, corresponded to a partial exchange of energy in which the medium is excited to or de-excited from an energy level $\hbar\omega_i$ above the ground state. To illustrate, the atoms in a molecule are constantly vibrating about their equilibrium positions with a definite frequency. When monochromatic light hits the molecule, the light can be scattered by a process in which its frequency is decreased or increased by exactly the vibrational frequency of the molecule. Thus a very weak new radiation is produced, which was not originally present in the light. The additional spectral lines occur in pairs displaced equally in frequency to the high- and the low-frequency sides of the exciting line, and are referred to, for historical reasons, as the anti-Stokes and the Stokes shift, respectively.

In the first complete account of the phenomenon, Raman showed that the effect is exhibited by gases, liquids, crystals and amorphous solids, and that it is a "phenomenon whose universal nature has to be recognized."[4] The new lines observed are characteristic of the scattering medium. The shift in frequency from the exciting line is independent of the frequency of the incident radiation. (Interesting exceptions to the rule of frequency independence are Brillouin scattering, Raman scattering associated with sound waves in condensed matter, and some cases in which zone-center optical phonons in crystals free of improper symmetry exhibit linear wavevector dependence.) The inelastic light scattering was soon designated the "Raman effect."

Until 1961 Raman spectroscopy was limited to rotational spectra of gases and vibrational spectra of gases, liquids and solids. When allowed by selection rules, rotational and vibrational transitions occur in the near- and far-infrared spectra. The coupling of the internal excitations with the incident electromagnetic radiation in Raman scattering occurs in a fashion fundamentally different from the direct emission or absorption of radiation caused by the de-excitation or excitation of the system; selection rules for Raman spectra are thus deduced from considerations different from those for infrared spectra. The polarization characteristics in the two phenomena also differ. Thus in many respects Raman spectroscopy is complementary to infrared spectroscopy. Moreover, the ease of conducting spectroscopic studies in the visible range was, and continues to be, an attractive feature of Raman spectroscopy.

With the invention of lasers, Raman spectroscopy reached a new level of sophistication. Raman spectra associated with polaritons, plasmons, magnons, Landau levels and electronic levels of ions and impurities in solids; Raman spectroscopy of molecules adsorbed on surfaces, surface excitations and samples subjected to ultrahigh pressures and magnetic fields; the stimulated Raman effect; and the spin-flip Raman laser—all are examples of the vastly expanded scope that resulted from the introduction of the laser.

Announcement and acclamation

Raman gave a full public account of his discovery in an address before the South Indian Science Association at Bangalore on 16 March 1928. The address, entitled "A

Robert A. Millikan with Raman in Bangalore in 1940. In 1924 Raman spent a few months at Caltech at Millikan's invitation. There the two developed a lifelong friendship. (Photo courtesy of the Archives of Caltech.)

New Radiation," was prepared as an article immediately on his return to Calcutta, and printed overnight. Reprints were posted the next day to scientists all over the world. Although many students participated in the events leading to the discovery of the Raman effect, Krishnan coauthored the short notes preceding the article and several definitive papers following it. In his address, Raman made a special acknowledgment of Krishnan's contribution, stating, "I owe much to the valuable cooperation in the research of Mr. K. S. Krishnan and the assistance of Mr. S. Venkateswaran and other workers in my laboratory."

In the 1920s studies on light scattering were being pursued in several laboratories throughout the world.[6] The younger Lord Rayleigh (England), Robert W. Wood at Johns Hopkins University (US), Jean Cabannes at the School of Science (Montpellier and Paris, France), and Grigorii Landsberg and L. Mandelstam at the Institute of Physics (USSR Academy of Sciences, Moscow) made significant contributions to the field. The possibility of inelastic light scattering was very much "in the air," and the French and Russian workers were close on Raman's heels. Indeed, the Raman effect was rediscovered independently by Landsberg and Mandelstam in crystalline quartz and calcite. That inelastic light scattering might be associated with internal excitations of the scattering medium was anticipated by Adolph Smekal; it is implicit in the dispersion theory of Hendrik A. Kramers and Werner Heisenberg.

The announcement of the Raman effect was hailed with great acclamation all over the world. Wood, famous for his important experimental accomplishments in the study of resonance radiation, sent the following cable to *Nature*:

> Professor Raman's brilliant and surprising discovery that transparent substances illuminated by very intense monochromatic light scatter radiations of modified wavelength and that [the] frequency difference between the emitted radiation and the one exciting the medium is identical with the frequency of the infrared absorption bands, opens up a wholly new field of study of molecular structure. I have verified this discovery in every particular. . . . It appears to me that this very beautiful discovery which resulted from Prof. Raman's long and patient study of the phenomenon of light scattering is one of the most convincing proofs of the quantum theory of light which we have at the present time.

It is of particular interest that the equipment Raman used in making his discovery was very simple, costing 500 rupees at the time—perhaps about $500 in current value.

In the years immediately following the discovery of the Raman effect, there was intense interest in its exploration and exploitation in numerous media as well as curiosity about its theoretical significance, and Raman's group continued to make important contributions. Recognitions and awards now came thick and fast. In 1924 Raman was elected a fellow of the Royal Society of London. He received the Matteucci Medal of the Societa Italiana della Scienza in 1928. The British government in India conferred knighthood on him in 1929. Also in 1929, the Faraday Society held a special symposium on the Raman effect, during which Raman gave an inspiring account of his discovery. The Royal Society awarded him the Hughes Medal in 1930—the same year he received the Nobel Prize in Physics for "his investigations on the scattering of light and the discovery of the effect known after him." He was only 42 years old. Accompanied by his wife, he traveled to Stockholm, where he received the prize on 10 December 1930. In anticipation, he had booked passage in July to ensure that they would have reservations on a ship that could get them to Stockholm by early December.

At this point in his career Raman occupied a very special position in the eyes of the Indian public. During the 1920s the Indian political movement toward complete independence from foreign rule had gathered significant momentum, spearheaded by political leaders like Mahatma Gandhi, Motilal Nehru and Jawaharlal Nehru. There was a great enthusiasm for, and commitment to, efforts to secure and improve national identity. In this context Raman's scientific accomplishments and the international recognition he received were cause for acclaim by his countrymen. He became a national hero, occupying a place in public esteem equal to that of Rabindranath Tagore, who had received the Nobel Prize for Literature in 1913.

Indian Institute of Science

In 1933 Raman was offered the directorship of the Indian Institute of Science, located in Bangalore in south India, in the Karnataka state. Bangalore is one of the most attractive cities in India; having flourished as part of the Princely State of Mysore, it is well laid out, with beautiful parks and many scientific and educational institutions, today including several "high-tech" industries. The Indian Institute of Science, now a premier scientific institution, was founded in 1909 by J. N. Tata, an industrialist known for his foresight, patriotism and philanthropy.

In 1933 the institute did not have a physics department. After some hesitation, Raman accepted the directorship and proceeded to establish an active center of physical research. He took on a large number of students and introduced them to challenging problems at the frontiers of physics. He had grand visions of transforming Bangalore into a center of excellence by international standards. Around the time he became director, many famous scientists were fleeing Germany, and Raman tried unsuccessfully to secure places for some of them at Bangalore, including Max Born and Erwin Schrödinger.

Despite his efforts to attract distinguished faculty, Raman's strong personality and management style caused serious difficulties with the institute's governing body, and he was forced to resign from the directorship after a few years. He remained at the institute as a professor of physics until 1948, and pursued new avenues. Light scattering continued to figure prominently in his research program.

One of Raman's outstanding contributions during his 15 years at the Indian Institute concerned the diffraction of visible light by high-frequency sound waves generated in fluids by a transducer. Peter Debye and Francis Sears in the US and Lucas and Biquard in France had reported observing beautiful Fraunhofer diffraction when monochromatic light propagated through a liquid cell normal to high-frequency sound waves generated with a quartz transducer. For sound waves of sufficient intensity, numerous orders of diffraction and a wandering of the intensity among the orders were seen in the richly detailed diffraction pattern. Before Raman and Nagendra Nath gave an explanation,[7] all the theories of the phenomenon were off the mark. Raman and Nath realized that the incident plane wave encounters the "phase grating" represented by the fluid in the ultrasonic field and is transformed into a "corrugated wave." All the details observed follow through quantitatively from their theory, which is closely analagous to that developed by Rayleigh in his book *Theory of Sound*. Raman and Nath published several beautiful papers that not only explained the observed effects but also opened up new avenues for development. Today this form of diffraction is of great interest for acousto–optical applications.

Raman and his students made a comprehensive study of diamond, a crystal that fascinated him all his life. His younger brother C. Ramaswamy, reported the first observation of the first-order Raman spectrum of diamond, which consists of a single line at 1332 cm^{-1}. S. Bhagavantam, another of Raman's students, also made extensive studies on the Raman spectrum of diamond, and Nagendra Nath identified the origin of the 1332-cm^{-1} line as a lattice vibration in which the two face-centered Bravais lattices vibrate rigidly against each other. R. S. Krishnan, who exploited the Rasetti technique that involves the 2537-Å resonance radiation of mercury, first observed the second-order Raman spectrum of diamond. Impressed by some of the sharper features of diamond's second-order spectrum, Raman ventured into the dynamics of crystal lattices and immediately involved himself in a bitter controversy with Born, Debye and others by criticizing their theories concerning lattice dynamics.

According to Raman, the normal modes of a crystal were to be enumerated by considering a supercell eight times the size of the primitive unit cell, yielding $24p-3$ discrete normal modes, where p is the number of atoms in the unit cell. The vibrational spectrum would then lead to a set of discrete frequencies, and Raman tried to identify these in a few crystals, such as diamond, NaCl and MgO. However, his view that the normal modes consist of only these discrete frequencies conflicted with the widely held Born–von Kármán theory of lattice dynamics, which predicts a continuous frequency spectrum. Indeed, the dispersion relations of lattice vibrations determined since the mid-1950s from inelastic neutron scattering are in excellent agreement with Born–von Kármán theory, and not at all with Raman's set of discrete frequencies. Raman claimed support for his theory from light scattering spectroscopy of crystals. The peaks in the second-order Raman spectrum of diamond that Raman said corroborated his theory are now regarded as consequences of van Hove singularities; they represent phonons at critical points having a large density of states that are typically associated with zone boundary phonons. Raman was incorrect, but he was adamant that he was right in his approach. This attitude made him highly emotional and irrational when it came to lattice dynamics. Further, it also proved counterproductive, as he got sidetracked into an area that was not his forte.

Raman had a lively and lifelong interest in diamond, and he built up an outstanding collection of specimens. He made many studies of its structure, luminescence, lattice dynamics and x-ray diffraction effects. Unfortunately he landed in controversy again when he proposed that diamond exists in two forms, one with tetrahedral and the other with octahedral symmetry, and that certain of its physical properties, such as its infrared and ultraviolet absorption, luminescence and optical birefringence, could be traced to this circumstance. However, in the early 1950s Walter Bond and Wolfgang Kaiser at Bell Labs showed that these properties were due to the presence of nitrogen as a substitutional impurity, and had nothing to do with the fundamental character of diamond. Similarly, the so-called extra spots observed in the Laue pattern of some diamonds, which Raman believed to be due to the excitation of optical phonons accompanying a Bragg reflection, were also precisely those associated with platelets of nitrogen impurities. Raman engaged in a long drawn-out controversy with Kathleen Lonsdale (University of London) over his "quantum x-ray reflections," and many roughly worded exchanges between the two appeared in the literature.

These controversies do not detract from the fine contributions to optics, spectroscopy and crystal physics that Raman made during these years. He and Nedungadi made the first observations and gave the first interpretation of the soft-mode behavior that drives the phase transition in quartz from the α to the β form, almost two decades before William Cochran published his soft-mode theory for phase transitions. Raman and his students made outstanding contributions to the physics of crystals, including, for example, their exquisite observation of conical refraction in naphthalene. During his tenure as professor at the Indian Institute of Science, the physics

Arnold Sommerfeld with C. V. Raman and K. S. Krishnan (left), in Calcutta during Sommerfeld's 1928 visit to Raman's laboratory. (Photo courtesy of Deutsches Museum, Munich, supplied by G. Torkar of Ludwig-Maximilians Universität, Munich.)

department was intensely active in diverse areas of physics, with Raman as its moving spirit.

Raman Research Institute

Raman had visions of establishing an institute where he would continue his scientific research after retiring from the Indian Institute. The Maharaja of Mysore donated a lovely 11-acre piece of land at one of the prime locations in Bangalore for this purpose. When Raman retired in 1948, the building for his new institute was nearing completion. Around this time he had an opportunity to visit the US as a member of the Indian delegation to the World Bank. After discharging his duties, Raman visited a few laboratories, including Bell Laboratories, and bought a lovely collection of minerals and gems that became the nucleus of a crystallographic and mineralogical museum at his new institute. The Raman Research Institute opened in 1949, with Raman as its director and as a professor, assisted by a small staff, including the authors of this article. Jayaraman was a close associate of Raman from 1949 to 1960, and Ramdas was Raman's pupil from 1950 to 1956.

Raman equipped his institute with beautiful museums, a lecture hall, an outstanding library, offices and laboratories, and once more he carried on his scientific work. He took on a few research students, but the institute was established primarily so that he could pursue his interests. Raman utterly enjoyed his investigations on gems and minerals, and between 1950 and 1960 he published a series of papers on the colors of gems and minerals, with some of us as collaborators, but more often by himself. This body of work reflects his taste for aesthetics in physics. He loved to demonstrate his findings to visitors, and to explain in simple language the most esoteric optical phenomena. Maharajas, Prime Ministers, politicians, officials, students and laymen came in throngs to visit the institute and to see Raman. His magnificent collection of gems and minerals and his inspiring tales enthralled them. From 1949 until his death in 1970, Raman enjoyed the research institute he built for himself. He filled the grounds with spectacular flowering trees, shrubs and, especially, roses. The finest roses the Bangalore nurseries could supply were planted under his supervision, and he admired them as a child admires a new toy. Raman knew the scientific names of most of the trees and shrubs on the institute's grounds.

The institute's museum contains a collection of beetles and butterflies, because Raman was fascinated with the colors of these insects. Among the most colorful butterflies are the *Morpho brazilius* and certain Himalayan species, which exhibit a spectacular blue iridescence. Raman studied these and wrote a paper entitled "Iridescent Colors Exhibited by Beetles and Butterflies." Desiring to add some local butterflies to his collection, he went to his country estate outside Bangalore and personally bagged butterflies with a butterfly net bag. Raman was, perhaps, the only Nobel Prize winning physicist to have engaged in chasing butterflies!

In the 1960s Raman became very interested in vision, and he thoroughly educated himself on the anatomy and physiology of the eye and its performance as a visual apparatus *par excellence.* He talked to visitors at his institute about rod vision, cone vision, color blindness and acuity of vision, and he carried out very simple experiments with color filters using himself and others as guinea pigs. He wrote a series of memoirs on his findings.

Raman bequeathed all his personal wealth to his institute, and he hoped for a bright future for it. He was very much against accepting government grants, for he feared that this practice would destroy the freedom necessary to carry out fundamental research. When India's education minister, M. A. Chagla, offered financial support from the Indian government, Raman said: "Sir, I want this institute to be an oasis in the desert, free from government interference and the application of its rules and regulations. That would destroy my institute. Thank you for your offer." After Raman passed away, his younger son, V. Radhakrishnan, an eminent radioastronomer, succeeded him as the director of the institute. In the past 18 years the institute has grown beyond anything Raman would have imagined, and it is now largely supported by grants from the government of India.

Raman and science in India

Raman created many scientific institutions in India and nurtured them into centers of research. He put new life into the Indian Association for the Cultivation of Science, organized and built the physics departments at the University College of Science and at the Indian Institute of Science, and founded the Raman Research Institute. With his strength of personality, vision and genius, and with discipline and dedicated work, he brought all of them world renown. One of his longest lasting contributions to Indian science is the large number of talented students whom he initiated into the excitement of research. Many of them in turn have created independent schools of research. Raman's influence will thus be felt in India for many generations.

Raman recognized the importance of scientific journals. In *Current Science* in May 1933 he wrote, "While the foundation of the scientific reputation of a country is established by the quality of work produced in its institutions, the superstructure is reared by the national journals which proclaim their best achievements to the rest of the world." Raman's contributions to scientific journalism in India include the *Bulletin of the Indian Association for the Cultivation of Science*, which was later transformed into *Proceedings of the Indian Association for the Cultivation of Science*, and still later into the *Indian Journal of Physics*. When he moved to Bangalore he launched and nurtured the *Proceedings of the Indian Academy of Sciences*. In 1932 he took an active part in starting *Current Science*, a journal styled after *Nature*. Raman strongly believed that the best work done in India should be published in Indian journals, and he set a personal example by publishing all his papers in the journals he started. The pages of the *Proceedings of the Indian Academy of Sciences* are filled with his work and the work of his students.

Recognizing the importance of a scientific body in arousing and maintaining public awareness of science and representing science to those in government, Raman founded the Indian Academy of Sciences in 1934. Outstanding scientists from all over India were elected fellows, and eminent scientists from around the world were invited to join a distinguished body of foreign fellows. Raman was elected founding president and held the office until his death. He also served as editor of the *Proceedings* and established the highest standards for the journal. The *Proceedings* appeared promptly every month in two sections—*A* for physical sciences and *B* for biological sciences—and were dispatched to subscribers in India and abroad. The *Proceedings* are considered among the top scholarly journals of the world; papers in physics currently appear in a new "reincarnation" called *Pramana*.

Raman meticulously organized the academy's annual meetings, with their attendant scientific programs and public lectures. The best work done by the fellows and their associates was presented at these meetings, and Raman's public lectures were usually the high points. The academy met at the invitation of a university serving as the host, so that young students of science were exposed to India's foremost scientists directly. Raman sat through all the sessions, both in the physical and the biological sciences, and added luster and humor to the proceedings. These annual meetings were jocularly referred to as "Raman's circus," and he never failed to be present, except once toward the end of his life. Since his death, the Indian Academy of Sciences has redoubled its activity and multiplied its publication efforts severalfold.

Some reflections on Raman's personality

Raman belonged to the fast-disappearing class of scientists who could properly be called natural philosophers. Far from favoring the extreme specialization that ultimately results in knowing "more and more about less and less," he believed that scientific endeavor should remove, not emphasize, the sharp boundaries between scientific disciplines.

Raman was, of course, the supreme egotist. But in private conversation he often showed such unbelievable humility as to make one wonder which was his true self. He was a man of emotion and could get greatly excited. But he had an excellent sense of humor and could keep an audience roaring with laughter by describing what might have been a commonplace incident. Above all he was a very simple man, almost childlike. During the memorial meeting for Einstein in Bangalore, Raman choked with emotion before he could begin his talk. He then proceeded to give an eloquent, spontaneous tribute highlighting Einstein's epoch-making achievements.

No single person has done as much for Indian science as Raman. Through his personal example of dedication; through his success as a teacher *cum* leader in training generations of physicists; through the creation of scientific institutions and facilities for research and the founding of scientific academies and journals; and through his gift of eloquence, Raman exercised a tremendous influence on the progress of science in India. In 1954 he was the obvious choice for the first presentation of the highest award given in independent India, the "Bharat Ratna," or Jewel of India. Prime Minister Rajiv Gandhi has declared 28 February "Raman Day," to remember him and to express the gratitude of the nation to this great savant of science.

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