Dr. C.V. Raman

(1888-1970)

Part II

by

L. A. RAMDAS

Preface

The present series of articles on Dr. C.V. Raman is addressed specially to the young scholars of the present and future generations, as well as to their teachers. The story of Raman, the man, the great teacher and the superb scientist is sure to inspire many generations of scholars in our land to emulate his shining example of life-long and single-minded dedication to science.

In the present part, after briefly dwelling on Raman in relation to his early pupils at Calcutta and touching on a few interesting episodes, we shall cover the most exciting period of his career which witnessed the discovery of the "Raman Effect" and won international fame for himself and the Calcutta School of Physics developed by him.

The period covered will be roughly 1921 to 1930, i.e., from the 33rd to the 42nd year of Raman's life.

1. Introduction

In part I we dealt with the rapid developmental phase of Prof. Raman's scientific career at Calcutta. We saw how enthusiastically the "Association" welcomed him into its fold, how he attracted the admiration of the leading educationists at Calcutta led by the late Sir Asutosh Mukerji and how he drew around himself a band of devoted pupils as the new (first) Palit Professor of Physics and Honorary Secretary of the Association and how his earlier researches had already won for him the Fellowship of the Royal Society of London.

2. Changes in his habits of life and work

Prof. Raman's first two visits abroad and the contacts he made with many scientific men and institutions during these visits brought about a very wholesome change in his habits and methods of work. Previously, he used to work away for very long spells without regard to day or night, oblivious to needs of food, rest, etc. After his foreign experiences, the pattern of his working became more regular and systematic. He took to business-like habits in getting through his very heavy work-load of scientific research and direction of his many pupils. Regular

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hours for meals and short spells of relaxation in the evenings must have been a great relief to Lady Raman.

After he became F.R.S., the authorities of the Calcutta University were pleased to augment Prof. Raman's salary. About 1924, he acquired a horse and carriage, thus freeing himself from dependence on taxis. The carriage was black while the horse was chest-nut brown. There was, of course, a syce to take care of both and to act as driver. It was a very presentable set-up. Often, while taking his evening drive, if Lady Raman was not accompanying him, he would invite one of his senior scholars to keep him company. I once accompanied him. The evening drive usually led to the Calcutta Maidan, stopping somewhere near the statue of Lord Kitchner or Lord Roberts. Getting down, Prof. Raman would take a brisk walk towards Fort William and then take some quick jerks of 'Kasrat' and 'Dand' for exercise. He would then walk back to his carriage and drive home. On the occasion when I was with him, while walking back to the carriage at a distance of half-a-mile, he suddently asked for the exact time. I said 7.20 p.m. He asked me if I had a watch. I said 'No' but pointed at the distant tower-clock of Whiteaway and Laidlaw. He said that it takes him exactly 12 minutes to cover the distance and would check if I was right. To my great relief the time was 7.32 when we reached the carriage! He complimented me on what he called my excellent eye-sight. On the return drive we had a very interesting discussion on our current researches at the Association during which many fresh lines of investigation cropped up. I did not know how the time passed. We arrived at the Association by 8 p.m. My home being close to Prof. Raman's we both went home by the famous back-gate for which I was one of the privileged few to possess the freedom of the key.

3. Prof. Raman and his pupils

The daily activities at the laboratories of the 'Association' usually started by 7 a.m. Having started an experiment, one would go on working until 1 p.m. After a quick lunch the scholars would be back by 2 p.m. and work on far into the evening and often until 9 or 10 p.m., until the job on hand had reached a satisfactory stage. Working at this furious rate it is no wonder that many of the pupils could work through 5 or 6 major investigations each year. Those who could not cope with such a fast tempo of work would automatically drop off.

By 1920, Prof. Raman had gathered round himself an increasing number of extremely bright and capable pupils so that, more and more, he could get his research programme executed rapidly by them. He inspired his scholars to use their own initiative and ingenuity to the fullest extent. He would see what was going on and discuss results at intervals. At any given time, however, he would concentrate his attention on the particular scholar who was then entering the most critical phase of his research. Interpretation of results, fruitful suggestions to carry the investigation several stages further and quick discussion of results already obtained for immediate publication resulted from this effective type of collaboration between the Professor and the pupil. Each of his pupils had his opportunity for such exhilerating collaboration at the developing phase of his investigation. All the time, the pupils enjoyed the fullest freedom to think, work and improvise for themselves. Spoon feeding of any kind was absolutely taboo. A spirit of perfect understanding and goodwill pervaded the entire 'Association', with Ashu Babu, the Assistant Secretary, ever ready to help us with any material or facility that we needed, the scholars themselves helping each other spontaneously.

Prof. Raman even at the comparatively young age of 34, had become a legendary all-India figure like poet Tagore, Dr. S. Radhakrishnan (later President of free India) and other public leaders that the freedom movement had thrown up. This is a position that a scientist of India today, however eminent, will find it hard, if not impossible, to attain. The press invariably kept in vigilant touch with Prof. Raman and was ever keen to report promptly on his latest investigations.

The numerous popular lectures that Prof. Raman readily gave before the vast and enlightened public of Calcutta and our other big cities in India won for him immense popularity and admiration. These lectures were illustrated with lively experimental demonstrations. They were replete with spontaneous jokes and were delivered in his high-pitched resonant voice which reached the entire audience (no loud-speakers then!). Rich in imagery and eloquence, the lectures were rendered in so popular a style that every listener felt that he understood all the science that the learned lecturer was discussing. This contact and rapport with the public helped greatly in winning for Science a worthy place in the scheme of things and for the gifted speaker a wonderful hold on the public imagination.

Such was Prof. Raman even at this early stage of his career. Though he was hardly 5 to 6 years older than his senior pupils (some of whom were even older than him), they used to feel a spontaneous reverence and profound respect for Prof. Raman, worthy of one twice his age! Prof. Raman, on his part, was, however, always accessible and quite informal.

Fig. 1 shows a group photograph taken in 1921, on the eve of Prof. Raman's departure to U.K. to attend the Congress of Universities of the British Empire held in Oxford. Here we see the Professor as the central figure (he was hardly 32 years of age then) in the company of senior pupils like Dr. N.K. Sethi, Dr. S.K. Banerji, Prof. V.S. Tamma, and others whose names are all mentioned below the photograph. The present writer then 20 years old and Mr. Sunderaraman are squatting on the lawn. Standing at the extreme right is dear Ashu Babu, Assist. Secretary of the Association, whose devotion to Prof. Raman had become a legend.

As already mentioned in Part I, Dr. N.K. Sethi completed a series of elegant studies in Optics during 1920-21 and won for himself the DSc of the Allahabad University within a year and a half of his arrival at Calcutta. At the time when this picture was taken, Prof. Raman had not yet embarked on his epoch-making researches on the scattering of light by molecules. These commenced, indeed, on his return voyage to India a few months later[1], in September 1921, when he was drawn to this important topic by the wonderful blue colour of the Mediterranean Sea, as mentioned earlier (Part I).

Fig. 2 is a later group photo taken many years later at Waltair at a session of the Indian Academy of Sciences in the late forties, and is reproduced here for the reason that many, if not all, of the most distinguished pupils of Prof. Raman who had been closely associated with him at Calcutta during the greater part of the nineteen twenties are present here. Sitting left to right we see Dr. A.S. Ganesan, Dr. L.A. Ramdas, Dr. K.S. Krishnan, Dr. KR. Ramanathan and Dr. S. Venkateswaran, with Prof. Raman at the centre. It will be appropriate here to dwell very briefly on just a few of these distinguished names as typical of the pupils of Prof. Raman during the period we are considering.

(*a*) *Mr. K. Seshagiri Rao:* He had joined as a Madras University Research Scholar by 1920 and was the first to conduct experimental studies on the scattering of light by water and a few other liquids, vapours and gases at atmospheric pressure.[2] Using monochromatic light from a quartz mercury lamp and estimating the absolute intensity of the light scattered

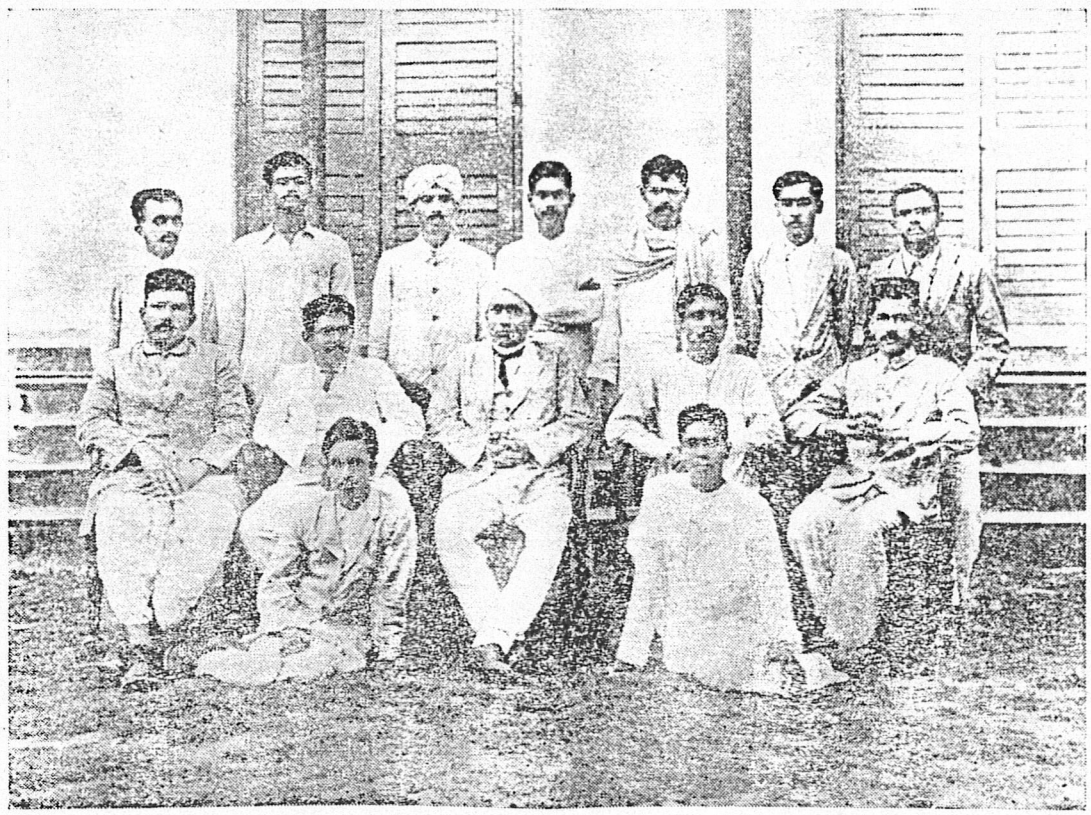
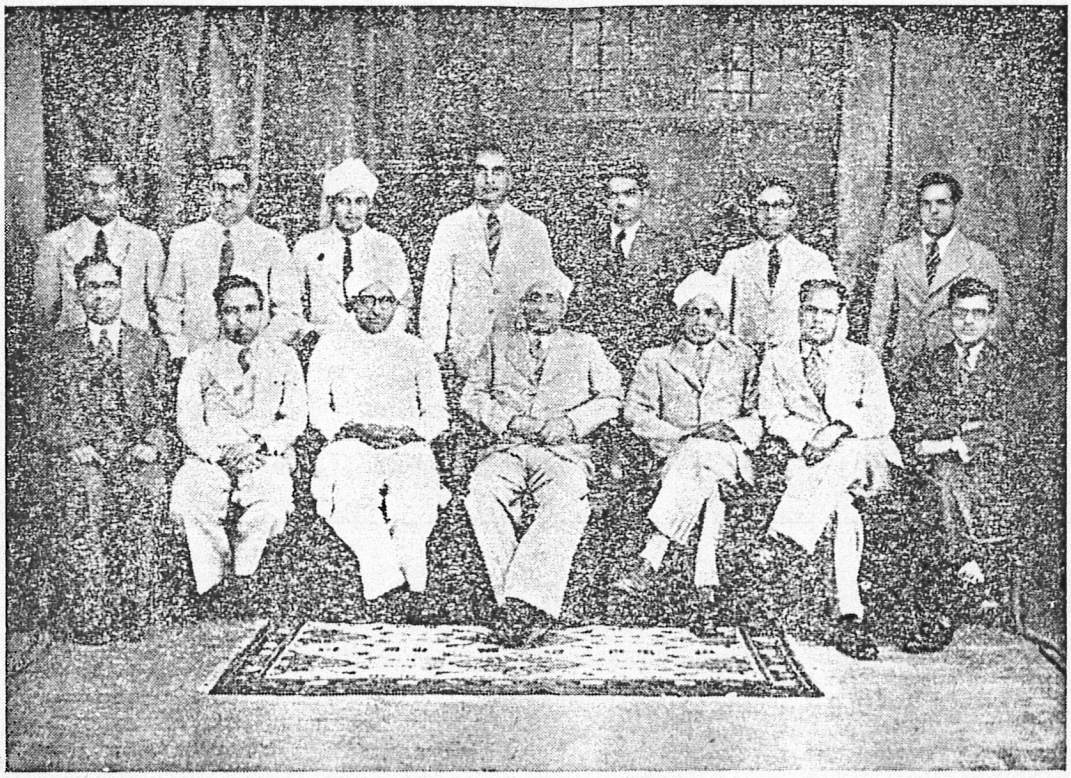


FIG. 1

Sitting (*left to right*): Prof: V.S. Tamma, Dr. S.K. Banerji, Prof: C.V. Raman, Dr. N.K. Sur and Dr. N.K. Sethi
Standing (*left to right*): Mr. K. Seshagiri Rao, Dr. Bidhubhushan Roy, Lala Govardhan Lal Dutta, Dr. Durgadas Banerji, Dr. Y. Venkatramayya, Dr. Panchanan Das, and Mr. Ashutosh Dey.
Squatting on the lawn (*left to right*): Dr. L.A. Ramdas and Prof. Sunderaraman.



Sitting (left to right): Dr. A.S. Ganesan, Dr. L.A. Ramdas, Nr. K.S. Krishnan, Prof. C.V. Raman, Dr. K.R. Ramanathan, Dr. S. Venkateswaran, and Mr. S.S. Moorthy Rao.

Standing (left to right): Dr. C. Ramaswamy, Dr. S. Bhagavantam, Dr. S. Paramasivan, Dr. Sreenivasa Rao, Dr. N.S. Nagendranath, Dr. R. Ananthakrishnan and Dr. C.S. Venkateswaran.

by water in all directions, Raman and Rao showed that this depletion of the incident energy is accounted for, as indeed Prof. Raman had shown earlier, by the Einstein-Smoluchowski formula, viz.

$$\alpha = \frac{8\pi^3 \, R \, T \, \beta \, (\mu^2 - 1)^2 \, (\mu^2 + 2)^2}{27 \, N \, \lambda^4}$$

where α is the depletion due to scattering in all directions during the passage of the incident beam through unit length of the medium, β is the compressibility of water, μ the refractive index, T the absolute temperature and R and N are the gas constant and the Avogadro's number per gramme-molecule. From their measurements of α with monochromatic light of wave-length 4358 A.U., Raman and Rao estimated the value of N as 7.3×10^{23}, which is of the right order of magnitude. This justifies the validity of the E.S. formula for dense media. They investigated also the scattering of light in a few liquids and vapours or gases.[6]) Mr. Seshgiri Rao soon left to take up appointment as an Examiner of Patents at Calcutta.

(*b*) *K.R. Ramanathan:* He arrived at Calcutta in December 1921 at the age of 28 years, as a Madras University Research Scholar. Ramanathan was intellectually very mature and was already well read in the available literature on molecular scattering of light. He joined the Association at a time when Prof. Raman was planning his pioneer researches on the Molecular Scattering of Light by all phases of matter, viz., the gaseous (also vapour), the liquid (including liquid mixtures) and solid states as well as the transition from gas-vapour to the liquid state. At the time when Ramanathan arrived, Prof. Raman was extremely busy writing up his well known book entitled "The Molecular Diffraction of Light" (Calcutta University Press, 1922) and Ramanathan was of considerable assistance to him in planning the exposition of some of the chapters of this remarkable publication which anticipated, with prophetic vision, the classical researches of the next decade or more. Ramanathan, a very fast and elegant experimenter, and a clear thinker, carried out in collaboration with Prof. Raman very striking investigations on the characteristics of the changes in the intensity and depolarisation of the light transversely scattered by liquids and dense vapours and gases during the passage, on heating, of ether, benzene and carbon-di-oxide

from their liquid state through their critical temperatures on to their vapour and gaseous states at high pressures. In three classical papers[3,4,5] they showed that the intensity of scattering is in good agreement with the E.S. formula particularly when a small correction is made for the contribution of the orientation scattering due to the un-symmetrical shape of molecules which adds an un-polarised component and the observed de-polarisation to the other-wise completely polarised scattering. Raman and Ramanathan also worked out two other important papers, one on light scattering by liquid mixtures[7] and the other on X-ray diffraction in liquids.[8] These indeed were starting points for a long series of papers published in the sequel by several workers at the Association. Ramanathan also worked out two theoretical papers,[9,10] on the 'Electromagnetic Theory of the Scattering of Light by Fluids' and compared the theoretical with the actually observed data. In the short spell of less than a year Dr. Ramanathan had submitted his DSc thesis to the University of Madras and was awarded this degree by that University as the very first recipient. No wonder that Prof. Raman held him in the highest regard. Dr. Ramanathan took up appointment as Lecturer of Physics at the University of Rangoon immediately after his DSc, but spent every vacation at the Association at Calcutta, breaking new ground with his usual speed. We shall revert to a most interesting result of his during the summer of 1923 later in this article. Dr. Ramanathan joined the India Meteorological Department in 1925 and brought immense credit to himself and that department by his distinguished researches in Atmospheric and Geo-Physics during the period 1925 to 1949. He later played a leading role in developing the new Physical Research Laboratories at Ahmedabad where he still guides a very large group of leading workers in Atmospheric-physics, Geo-Physics, Ionospheric and Stellar Physics in relation to the conducting layers of the Upper Atmosphere.

(*c*) *Mr. J.C. Kameswara Rav.*: As a Palit Research Scholar under Prof. C.V. Raman, he followed up the work of Raman and Ramanathan on liquid mixtures by investigating the opalescence of binary liquid mixtures of Methyl Alcohol and Carbon-di-sulphide[11]) (partially miscible in each other) and of Toluene and Acetic acid (wholly miscible in each other) and showed that the experimental results were in fairly good agreement with the theoretical formula when account is taken of the scattering due to density and concentration fluctuations and of the anisotropy of the component molecules. The Calcutta University awarded him the DSc degree on the basis of the above work. Dr. Rav later joined as a professor of Physics at Hyderabad.

(*d*) *L.A. Ramdas*: He joined the Association as Palit Research Scholar under Prof. Raman in March 1923 and within two months, in May 1923, succeeded in observing the Scattering of Light by a pure Mercury surface and by other pure liquid surfaces. In his Annual Report for 1925[12]), as Honorary Secretary of the Association, to its Committee of Management, Prof. Raman referred to Ramdas's work on this phenomenon in the following terms (vide Indian Journal of Physics, Vol. I, pt 2, page 98, 1925) :—

> " .....
> During the past few years the molecular scattering of light in fluids, viz., gases, vapours and transparent liquids, has become a familiar subject in our laboratory. This phenomenon, which gives rise to the blue colour of the sky and of the sea, is a volume effect. Another equally important phenomenon was discovered, in the course of work undertaken in our laboratory, by Mr. L.A. Ramdas during the summer of 1923. This phenomenon is the Scattering of Light by the free surfaces of a great variety of liquids and has been extensively investigated by Mr. Ramdas..."

Besides the series of papers[13,14,15,16] on the above phenomenon, Ramdas also investigated the optical properties of monomolecular films[20] spreading on a clean water surface and the spontaneous movements of surface active substances like camphor, amyl alcohol, etc. due to excess of surface pressure in front of concavities at the edges of these floating substances in contact with clean water surfaces[17]. He also investigated the colours of potassium chlorate (twin) crystals[18] and the spectrum of potassium burning spontaneously in an atmosphere of chlorine.[19] For his thesis entitled "The Scattering of Light by Liquid Surfaces and other allied Phenomena" he was awarded the Ph.D degree by the Calcutta University. Though he joined the Indian Meteorological Service in 1926, Dr. Ramdas spent his leave periods at the Association continuing his research work in Physics. His work in the Meteorological Department was mainly of the research type; he commenced and developed the new Division of Agricultural Meteorology at Poona which specialised in the physics of the Earth-Atmospheric boundary layers, a field in which he is recognised as a pioneer. After retiring from Meteorology, Dr. Ramdas continued his researches in Physics and Atmospheric Physics at the National. Physical Laboratory at New Delhi where he still continues working as a scientist emeritus.

Reference will be made later to his investigation of 1928 when he spent his leave at the Association.

(e) *K.S. Krishnan:* Krishnan joined the Association, as one of its research scholars, rather late in 1923. His first research was to examine the finding of Glaser that in gases at a sufficiently low pressure the molecules orient themselves in a strong magnetic field.[20] Using two long glass tubes of exactly equal length closed by optically parallel glass plates, one of them being kept in a magnetic field and the other outside it, both being filled with gas at the same pressure, and using the Rayleigh's refractometer technique, Krishnan showed conclusively that at no pressure does the interferometer fringe system show the slightest shift, thus proving that Glaser's conclusion had no basis at all. The next big problem that Krishnan undertook was to make an extensive survey of light scattering viz., intensity and % of depolarisation and of their variations with wavelength (colour). He took very careful measurements of these factors in respect of 65 dust-free liquids.[21] In the course of this investigation, like Ramanathan earlier in the case of water, Krishnan observed that in the case of some liquids, viz., water, ether, all the mono-hydric alcohols, benzyl and benzal chlorides, etc., the molecularly scattered light at right angles to the incident beam exhibited a feeble fluorescent component. We shall refer to this result later on in this part. Krishnan then took up a critical and detailed comparison of the theories of light scattering already put forward by Ramanathan, King and Cabannes,[22] concluding that more experiments are needed to judge their relative merits.

Prof. Raman and Krishnan, in a series[23,24,25] of papers discussed the magnetic double-refraction in liquids and the electric double refraction in relation to the polarity and optical anisotropy of molecules. At this stage it may be mentioned that Krishnan's fine record of research won for him first the MSc and later the DSc on the basis of theses submitted to the Madras University. His collaboration with Prof. Raman continued for many more years during the discovery of the Raman Effect and later, up to 1930, when he accepted the Reader-ship in Physics at the Dacca University and continued there his remarkable series of studies on the Magnetic Succeptibility of many organic and inorganic compounds with a band of scholars who joined him for post-graduate work. In the sequel he returned to the Association in 1933, as the first Mahendralal Professor, when Professor Raman left Calcutta to take up the Directorship of the Indian Institute of Science. A few years later Krishanan won the FRS. After a spell of very distinguished work as Professor of Physics at Allahabad, (1942–1947), he was awarded the knighthood by the British Government. Soon after, in 1947, he accepted the invitation to the Directorship of the new National Physical Laboratory in New Delhi, a position he held until his unexpected passing away in 1961, full of honours and distinctions. A detailed account of his eminent and distinguished career will be the work of his biographer. We shall later in this article quote in Professor Raman's own words about Krishnan's collaboration with him in the momentous researches leading to the discovery of the Raman Effect.

(*f*) *S. Venkateswaran*: Venkateswaran is, after Prof. Raman earlier in the second decade of this century (see Part I), the most outstanding example of a part time worker, who, after gruelling whole time routine in Government service, out-did many a whole time researcher by working in the evening hours and late into the night, on holidays and leave periods with extraordinary dedication and devotion to research, over more than a decade.

He joined the Association as an overtime worker in 1923 and began a series of remarkable investigations on the hitherto unexplored problem of molecular scattering of light in aqueous solutions[26,27] of the acids and other compounds and later in pure liquids. He won the MSc and later on the DSc of the Madras University by submitting theses covering his many important research papers and, as will be mentioned later in this article, played an important part by bringing the rather conspicuous "so called fluorescence" exhibited by pure, dry, distilled glycerine to the notice of Prof. Raman. This indeed revived urgent urge to explain this feeble fluorescence and very soon led Prof. Raman to the discovery of the Raman Effect.

Amidst his researches, this indefatigable worker found time to take his bachelor's degree in Law. He later joined the Patents Office at Calcutta. The creation and development of the Trade Marks Registry in India is entirely due to Dr. Venkateswaran's imagination and drive. Towards the closing years of his government service he had not only organised the Trade Mark Registry on an all-India basis, but also taken charge of both the Patents and Trade Marks Offices. Venkateswaran's example of assiduous striving and achieving against the greatest odds is indeed an inspiring one.

(*g*) *A.S. Ganesan*: Mr. Ganesan came to the Association by 1923 and immediately took up the study of light-scattering in liquids and gases at various angles[28] with respect to the direction of the incident beam of light. He showed that the variation of the intensity with angle in the case of polarised light is according to the simple formula

$$I\phi = I_o (1 + \cos^2 \phi)$$

whereas in the case of scattering of unpolarised light with depolarisation r of the scattered light, the variation of intensity is according to the formula

$$I\phi = I_o \left[1 + \frac{1-r}{1+r} \cos^2 \phi \right] \text{cosec } \phi.$$

He was awarded a research scholarship by the Madras University and studied the optical anisotropy of a series of organic vapours[29] from his measurements of the depolarisation of the molecular scattering of light by these vapours. He soon left on a Dominion Scholarship to undertake spectroscopic research at the London University. He took his Ph.D there but returning to India resumed research work at the Association at Calcutta. Special mention may be made of the Memoir on the Raman Effect[30] in liquids which he published in collaboration with Dr. Venkateswaran and of the Bibliography[31] of 150 papers on the Raman Effect prepared by him.

Dr. Ganesan continued his research activities when he joined the College of Science at Nagpur as professor. After retirement he is now editing "Current Science" at Bangalore, thus continuing to serve Indian Science.

(*h*) *I. Ramakrishna Rao:* He joined the Association about 1925 and after completing studies in laminar diffraction,[32,33] accomplished important research in light-scattering by 10 gases and vapours of 63 organic compounds and on the optical anisotropy of atoms and molecules. He took his Ph.D by thesis from the Calcutta University and later the D.Sc in London University. Raman Effect in ice and quartz [34] which he investigated showed that in the case of ice the Raman frequencies are sharper and of shorter wavelength than in liquid water. Dr. Rao soon after joined the Andhra University where he lectured and researched in Physics. After retiring, he has been keenly interested in manufacture of scientific instruments and appliances.

(*i*) *S. Bhagavantam*: He joined the Association at the comparatively young age of 18, Prof. Raman intuitively recognising in him great potentiality and precocity. As he arrived at Calcutta only towards the close of the period we are discussing in this article, we shall describe in the third part of this series how rapidly he developed as a first rate investigator in Physics and what a spectacular career he had, much to the admiration of his scientific colleagues and collaborators.

In the above brief references attention has been confined just to a few typical pupils of Prof. Raman who had collaborated with him in the various investigations on light scattering which culminated in Prof. Raman's discovery of the Raman Effect. We may have occasion to refer in subsequent articles to many of his pupils who conspicuously distinguished themselves in other fields of Physics in which Prof. Raman directed important researches.

4. Coming events cast their shadows before

From the preceding paras we have already seen that the "feeble fluorescence" observed by Ramanathan in 1923 and a year later by K.S. Krishnan had been noted as something to be clarified as it were. Though the Compton Effect had been discovered in 1922, the Nobel Prize was actually awarded to Prof. Compton in 1927. How this event excited Prof. Raman's imagination is best told by quoting from an 'eye witness' account recently communicated to me by Shri. B.N. Sreenivasiah, one of the pupils of Prof. Raman at Calcutta:—

"On a December evening in 1927, while I was at Calcutta after an examination and interview at Delhi, I visited the Association at Calcutta to pay my respects to Prof. Raman. His elder brother, Shri C. Subramanya Iyer (father of the famous Astrophysicist, Dr. S. Chandrasekhar) was also with Professor Raman when I entered his office. Soon after I went in, Dr. K.S. Krishnan rushed in and excitedly informed Professor of the announcement in the evening papers that Prof. A. H. Compton had been awarded the Nobel Prize in Physics for his discovery of the Compton Effect in X-Rays. On hearing this news, Prof. Raman beamed with delight and burst out in his characteristic fashion: "Excellent news.....very nice indeed. But look here Krishnan. If this is true of X-Rays, it must be true of Light too. I have always thought so. There must be an Optical analogue to Compton Effect. We must pursue it and we are on the right lines. It *must* and shall be found. The Nobel Prize must be won' ". And Mr. Sreenivasiah records how hardly within a few months he was attending an address Prof. Raman was delivering at Bangalore on "the New Radiation"!

5. The Discovery of the "Raman Effect"

The story of this discovery is best told in Prof. Raman's own words. We quote from his 'Nobel Lecture' delivered in Stockholm on the 11th December, 1930, i.e., two years after the discovery:—

"..... the possibility that the corpuscular nature of light might come into evidence in scattering was not overlooked and was in fact discussed in the essay of February 1922 [35] which was published at least a year before the well-known discoveries of Compton on X-Ray scattering. While our experiments in the main appeared to support the electromagnetic theory of light, evidence came to hand, at a very early stage of the investigations, of the

existence of a phenomenon which seemed to stand outside the classical scheme of thought. The scattering of light in transparent fluids is extremely feeble, much weaker in fact than the Tyndall effect usually observed in turbid media. It was experimentally discovered that, associated with the Rayleigh Einstein type of molecular scattering, was another and still feebler type of secondary radiation, the intensity of which was of the order of magnitude of a few hundreths of the classical scattering and differed from it in not having the same wavelength as the primary or incident radiation. The first observation of this phenomenon was made in Calcutta in April 1923 by Ramanathan who was led to it in attempting to explain why in certain liquids (water, ether, methyl and ethyl alcohols) the depolarisation of scattered light varied with the wavelength of the incident radiation. Ramanathan found that after exhaustive chemical purification and repeated slow distillation of the liquid in vaccum, the new radiation persisted undiminished in intensity, showing that it was a characteristic property of the substance studied and not due to any fluorescent impurity. Krishnan observed a similar effect in many other liquids in 1924, and a somewhat more conspicuous phenomenon was observed by me in ice and optical glasses. The origin of this phenomenon naturally interested us. .....

.....

This problem was taken up again by Krishnan towards the end of 1927. While his work was in progress, the first indication of the true nature of the phenomenon came to hand from a different quarter. One of the problems interesting us at this time was the behaviour of light scattering of highly viscous organic liquids which were capable of passing over into the glassy state. Venkateswaran undertook to study this question, and reported the highly interesting result that the colour of sunlight scattered in a highly purified sample of glycerine was a brilliant green instead of the usual blue. The phenomenon appeared to be similar to that discovered by Ramanathan in water and the alcohols, but of much greater intensity, and, therefore, more easily studied. No time was lost in following up the matter. Tests were made with a series of filters transmitting narrow regions of the solar spectrum and placed in the path of the incident beam, which showed in every case the colour of the scattered light was different from that of the incident light, and was displaced towards the red. The radiations were also strongly polarised.

.....

The work of Compton had made familiar the idea that the wavelength of light could be degraded in the process of scattering, and the observations with glycerine suggested to me that the phenomenon which had puzzled us ever since 1923, was in fact the optical analogue of the Compton Effect. The idea naturally stimulated further investigation with other substances.

The chief difficulty which had hitherto oppressed us in the study of the new phenomenon was its extreme feebleness in general. This was overcome by using a 7-inch refracting telescope in combination with a short-focus lens to condense sunlight into a pencil of very great intensity. With these arrangements and using complimentary light-filters in the path of the incident and scattered beams, as was done by Ramanathan in 1923, to isolate the modified radiations, it was found that they could be readily observed in a great many liquids, and that in many cases they were strongly polarised. Krishnan, who very materially assisted me in these investigations, found at the same time, that the phenomenon could be observed in several organic vapours, and even succeeded in visually determining the state of polarisation of the modified radiations from them. Compressed gases such as CO_2 and N_2O, crystalline ice and optical glasses also were found to exhibit the modified radiations. These observations left little doubt that the phenomenon was really a species of light-scattering analogous to the Compton Effect.

Its Spectroscopic Characters

Thanks to the vastly more powerful illumination made available by the 7-inch refractor, the spectroscopic examination of the effect, which had been abandoned in 1925 as indecisive, now came within the reach of direct visual study. With a Zeiss cobalt-glass filter placed in the path of the incident beam, and one or other of a series of organic liquids as the scattering substance, a band of blue-green region was observed by me in the spectrum of the scattered light, separated by a dark interval from the indigo-violet region transmitted by the filter. *Both* of these regions of the spectrum became sharper when the region of transmission was narrowed by the insertion of an additional filter in the incident beam. This suggested the employment, instead of sunlight, of the highly monochromatic radiations given by a mercury arc in combination with a condenser of large aperture and a cobalt-glass filter. With these arrangements, the spectrum of the scattered light from a variety of liquids and solids was visually examined, and the startling observation was made that the spectrum generally included a number of sharp lines or bands on a diffuse background which were not present in the light of the mercury arc.

The quartz mercury lamp was so powerful and

convenient a source of monochromatic illumination that at least in the case of liquids and solids, photographing the spectrum of the scattered light was found to present no extraordinary difficulties. The earliest pictures of the phenomenon were in fact taken with a portable quartz spectrograph of the smallest size made by the firm of Hilger. With a somewhat larger instrument of the same type, Krishnan obtained very satisfactory spectrograms with liquids and with crystals on which measurements of the desired precision could be made, on which the presence of the lines displaced towards the violet was first definitely established. The experimental difficulties were naturally greater in the case of gases or vapours, though they could be lessened by working with the substance under pressure. With an improvised instrument of large aperture (F/1.8), Ramdas obtained the first spectrograms with a gaseous substance (ether vapour) at atmospheric pressure.

The work of Compton had gained general acceptance of the idea that the scattering of radiation is a unitary process in which the conservation-principles hold good. Accepting this idea it follows at once that, if the scattering particle gains any energy during the encounter with the quantum, the latter is deprived of energy to the same extent, and accordingly appears after scattering as a radiation of diminished frequency. From thermodynamic principles, it follows that the reverse process should also be possible. Adopting these ideas the actual observations could be interpreted and the agreement of the observed displacements with the infra-red frequencies of the molecules made it clear that the new method opened up an illimitable field of experimental research in the study of the structure of matter".

Although short interim articles had been published in 'Nature' [36], [37], [38] as the above investigations got into stride and the discovery of the new Radiation was announced on the 28th February, the full picture of the new phenomenon was first presented by Prof. Raman in the inaugural address that he delivered before the South Indian Science Association at Bangalore on the 16th March, 1928. This address entitled "A New Radiation" [39] was written out immediately on his return to Calcutta and printed overnight by the courtesy of the Calcutta University Press (see Indian Journal of Physics, Vol. II, pt. 3, 1928). Thousands of reprints of this unique article were posted the same day to scientists all over the world. This characteristically prompt action of Prof. Raman fully ensured his priority for this famous discovery.

Fig. 3 shows, as typical of the earliest spectrograms recorded at Calcutta, (a) the spectrum of the source, viz., the Mercury Arc, (b) the spectrum of the light scattered by Benzene liquid, (c) by Toluene liquid, and (d) by Pentane liquid, respectively. Comparing the last three spectra with that of the source at the top of the figure, one notices many new lines which are characteristic of these substances and are not present in the incident light.

Fig. 4 is a micro-photometer record of the spectrum of Benzene shown in Fig. 3 (b). The record clearly shows the wavelenths and intensities of the incident and the new or modified lines.

Figures 3 and 4 are taken from Raman and Krishnan's paper [40] entitled "A New Class of Spectra due to Secondary Radiation" published in the Indian Journal of Physics, Vol. II, pt. 4, 7th May, 1928. In concluding this important paper, published so soon after the announcement of the discovery, Raman and Krishnan state the most important features of the new radiation as follows:—

(i) A large number of new lines are observed in the scattered spectrum which are not present in the original spectrum.

(ii) Each liquid shows a distinctive scattered spectrum, but certain similarities are exhibited by liquids having chemically similar groups in their composition.

(iii) The scattered spectrum of Benzene when observed with single line filters in the path of the incident light, shows that corresponding to each unmodified line in the spectrum, there are seven modified lines observable, of which two are specifically prominent. The frequency differences between the unmodified lines and corresponding modified lines are independent of the wavelength of the incident lines.

(iv) Six out of the seven in the group of modified lines have frequencies lower than that of the exciting line, while one has a higher frequency, the increase of frequency being numerically the same for it as the decrease of wave number for one of the six lines of degraded frequency.

(v) The shift of frequency of the modified lines is found to agree with certain characteristic infra-red frequencies of the molecule and in fact the method is capable of yielding extremely accurate measurements of these frequencies.

(vi) The observations are explicable on the supposition that the incident quantum of radiation may be absorbed in part and scattered in part by the molecule. If the molecule is initially in the normal state, the transition induced by the radiation must naturally be to a higher level of energy and hence the scattered radiation will have a degraded frequency. But if the molecule is initially in a level of energy

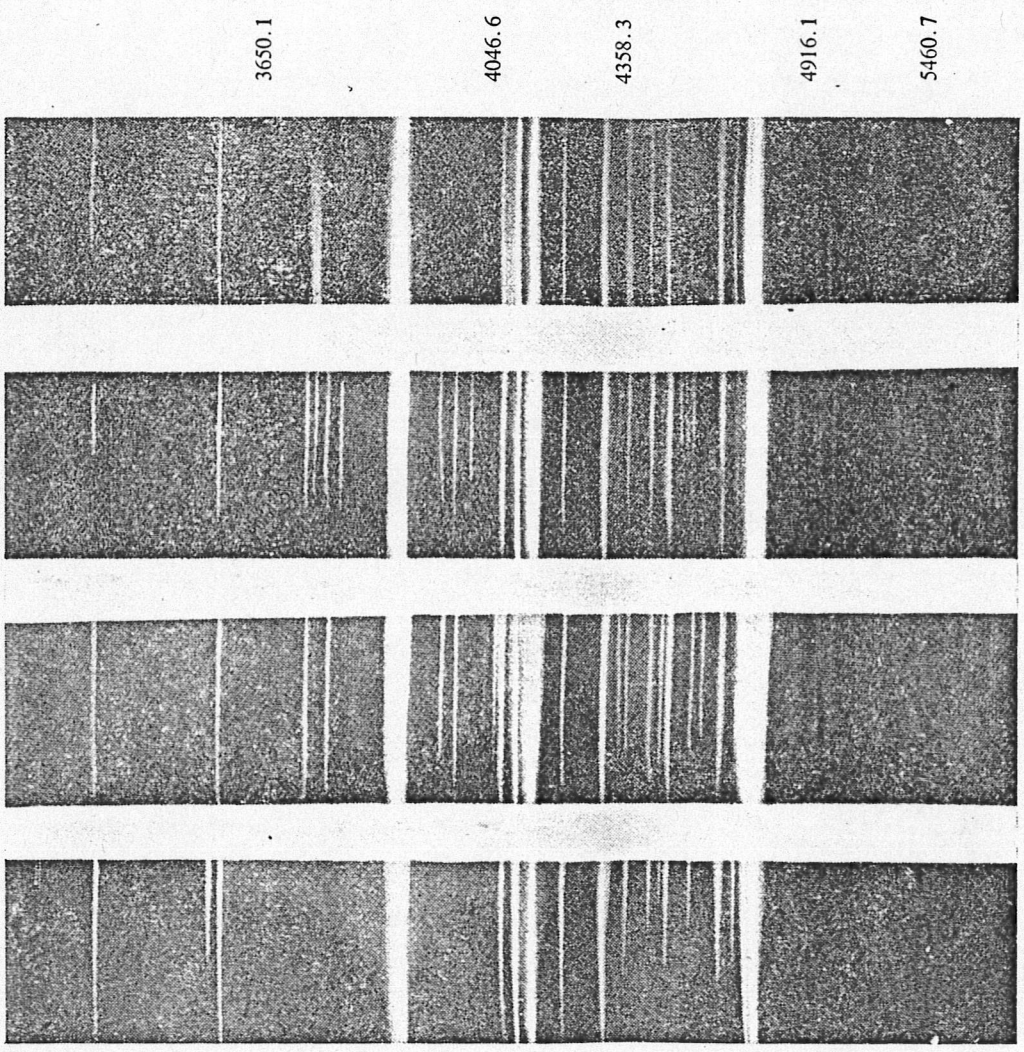
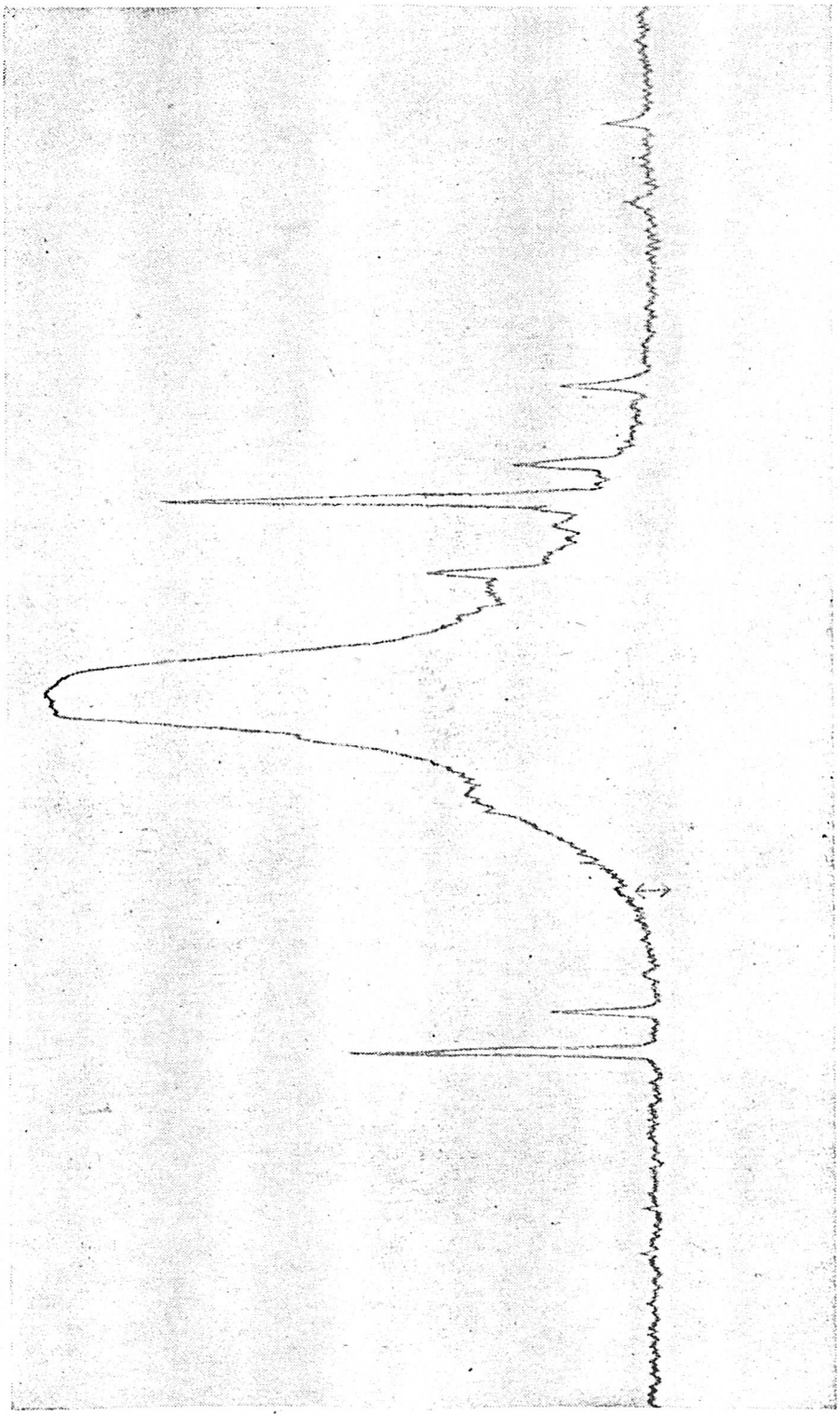

3650.1
4046.6
4358.3
4916.1
5460.7
(a) Hg are
(b) Benzene liquid
(c) Toluene liquid
(d) Pentane liquid

FIG: 3

Modified lines

Incident lines



5029.6

4916.1

4683.5

4593.9

4555.1

4476.4

4538.3

4178.5

4108.9

4077.8

4046.6

FIG: 4
Benzene

higher than normal, the radiation will induce a return to the normal level, and in this case we get a modified scattered radiation of higher frequency than the incident. The probability of such negative transitions induced by radiation is proved by the observations. The comparative feebleness of the modified line of higher frequency is readily explained on a thermodynamic basis.

It may be of interest to state here that the present writer's study of the modified spectra from liquid ether and its vapour respectively (see "The Raman Effect in Gases and Vapours" [41] by L.A. Ramdas, Ind. Jour. of Phys, Vol. III, pt. 1, p. 131, 1928) showed that while the increase of intensity of the unmodified or Rayleigh scattering from vapour to the liquid state is much less owing to the role of aggregation in the liquid, the increase in intensity of the modified line from the vapour state to the liquid state is greater, being proportional to density, and showing that the new radiation is indeed from the individual molecule and independent of the state of matter.

Another point of interest is that the discovery was *for the first time designated as the "Raman Effect" in a letter to Nature by the present writer communicated on 29th May, 1928* and published in 'Nature', Vol. 122, p. 57, 14th July, 1928.[42]

6. The discovery of the Raman Effect attracts world-wide attention

No sooner than the announcement of his discovery was made by Raman, scientists all over the world began to investigate the phenomenon and contribute to the rapidly increasing literature on this topic. By 1st August, 1929, Dr. A.S. Ganesan had already published a list of 150 papers on the effect. [31] Within hardly another year, by 1930, Dr. S. Bhagavantam, [43] could list as many as 400 papers published on the Raman Effect. With its many applications to Physics and Chemistry and Technology, the number of papers on this topic has been increasing in an ever accelerated manner. And, of late, with the discovery of the "Laser", a very power ful source of mono-chromatic radiation, and high resolution spectrographs, there has been considerable revival of interest in the discovery of hitherto undiscovered features of the Effect. All this cannot be detailed in the very short review attempted in this article.

7. Honours and Distinctions

The discovery of the "Raman Effect" brought great prestige to Prof. Raman and indeed put India on the scientific map of the world. Prof. Raman was knighted in June 1929. More honours and distinctions were showered on him. He was General President of the Indian Science Congress in January, 1929. The Italian Society of Rome awarded the Matteucci Gold Medal. He was invited to open a discussion on "Molecular Structure and Molecular Spectra" by the Faraday Society of England in August 1929. Lady Raman accompanied him on this trip. In 1930, the Royal Society of London conferred on him the Hughes Medal for his distinguished work in Optics. During the award-giving ceremony, Lord Rutherford made the following citation:—

"Sir Venkata Raman is one of the leading authorities in Optics, in particular on the phenomenon of the scattering of light. In this connection, about three years ago, he discovered that the light's colour could be changed by scattering. This had been predicted some time before, but in spite of search, the change had not been found. The RAMAN EFFECT must rank among the best three or four discoveries in Experimental Physics in the last decade. It has proved and will prove, an instrument of great power in the study of the theory of solids. In addition to important contributions in many fields of knowledge, he has developed an active school of research in Physical Science in the University of Calcutta".

We shall have occasion to list the numerous distinctions, honours and honorary doctorates that came to Prof. Raman in a later article of this series.

8. The Award of the NOBEL PRIZE in 1930

The news of the award to Prof. Raman of the coveted Nobel Prize was hailed universally by his countrymen with tremendous enthusiasm. Prof. Raman soon left for Stockholm to receive the Nobel Prize on the 10th December, 1930, when he was 42 years of age. He was accompanied by Lady Raman. We are fortunate in having a vivid eye-witness account of this visit and the Nobel Ceremony at Stockholm from Lady Raman whose account was published in the "Raman Number" of the Calcutta Municipal Gazette when the Calcutta Corporation presented an "Address to Prof. Raman in 1931. This article is entitled "A week in Stockholm" we quote below a few extracts from her most fascinating account:—

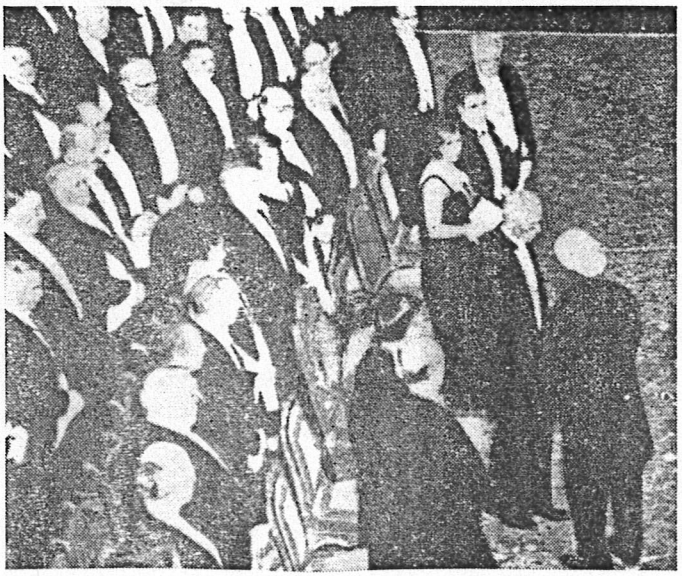
".....Our stay in Stockholm extended for a week from the 9th to 16th December, 1930. We arrived by train at Stockholm, the capital city of Sweden, at 8 O'clock in the morning of the 9th December. The platform was crowded with people waiting to receive the guests.....
.....Not being white-skinned, we could not mix with the natives of the country without being recognised, moreover our multi-coloured Indian dress was making us conspicuous to every eye.....It

was very difficult to get rid of the newspaper men. They must hear about Indian politics; my husband talked about educational matters but what was I to talk about? I could only speak on the habits, customs and beliefs of our country. It certainly interested them.

After referring to the tea at the British Embassy and the dinner at the Swedish Academy of Sciences to which Professor and Lady Raman were escorted by Dr. E.Nobel, a relative of Alfred Nobel, Lady Raman portrays the events during the Nobel Prize Award Ceremony in the following words:—

"The award of the Nobel Prizes took place on the 10th between 4 and 7 p.m. If I shut my eyes, I can

The Nobel Prize Award Ceremony, Stockholm, 1930



Sir C.V. Raman receiving the Prize.
The entire assembly stood up as Sir C.V. Raman received the Prize from the hands of the King of Sweden

FIG: 5

still see as in a dream the great concert hall of Stockholm, decorated with flowers and flags, filled with more than 4,000 people, the King and Queen of Sweden and the Royal family occupying the first seats (see top of fig. 5 of this article.) The Nobel Laureates then entered the Hall, each accompanied by a Professor in his own subject and followed by such Nobel Laureates of previous years as were present in Stockholm and the members of the Academy. As the procession entered, the whole audience stood up and remained standing until the Laureates took their seats amidst a fanfare of trumpets. The Laureates of the year were seated in one side of the dais and their introducers on opposite side. The Secretary of the Academy of Sciences read a report and gave a brief account of Nobel's life. Dr. Pleijel, Professor of Electro-Technics in the University of Stockholm, then rose and spoke for twenty minutes on my husband's investigations on the scattering of light and the new effect that had been discovered by him, and addressing him said: 'Sir Venkata Raman: The Royal Academy of Sciences has awarded you the Nobel Prize in Physics for your eminent researches on the diffusion of light and for your discovery of the effect that bears your name. The Raman Effect has opened new routes to our knowledge of the structure of matter and has already given most important results. I now ask you to receive the prize from the hands of His Majesty'.

On Sir Chandrasekhara rising to receive the Prize, the whole audience including the King stood up and the British flag was held aloft. The Laureate then approached the Royal Seat and bowed before the King who took him by the hand and presented him the Nobel Medal, Prize and Diploma. (See bottom of Fig. 5 of this article). This was attended with loud cheering and was followed by orchestral music for about fifteen minutes. (Fig. 6 of this article shows the inner side of the Nobel Prize Diploma).

Then followed in succession the addresses on the work of the other Laureates and the award of the medal, prize and diploma to each of them (see group of all the Laureates at top of Fig. 7 of this article).

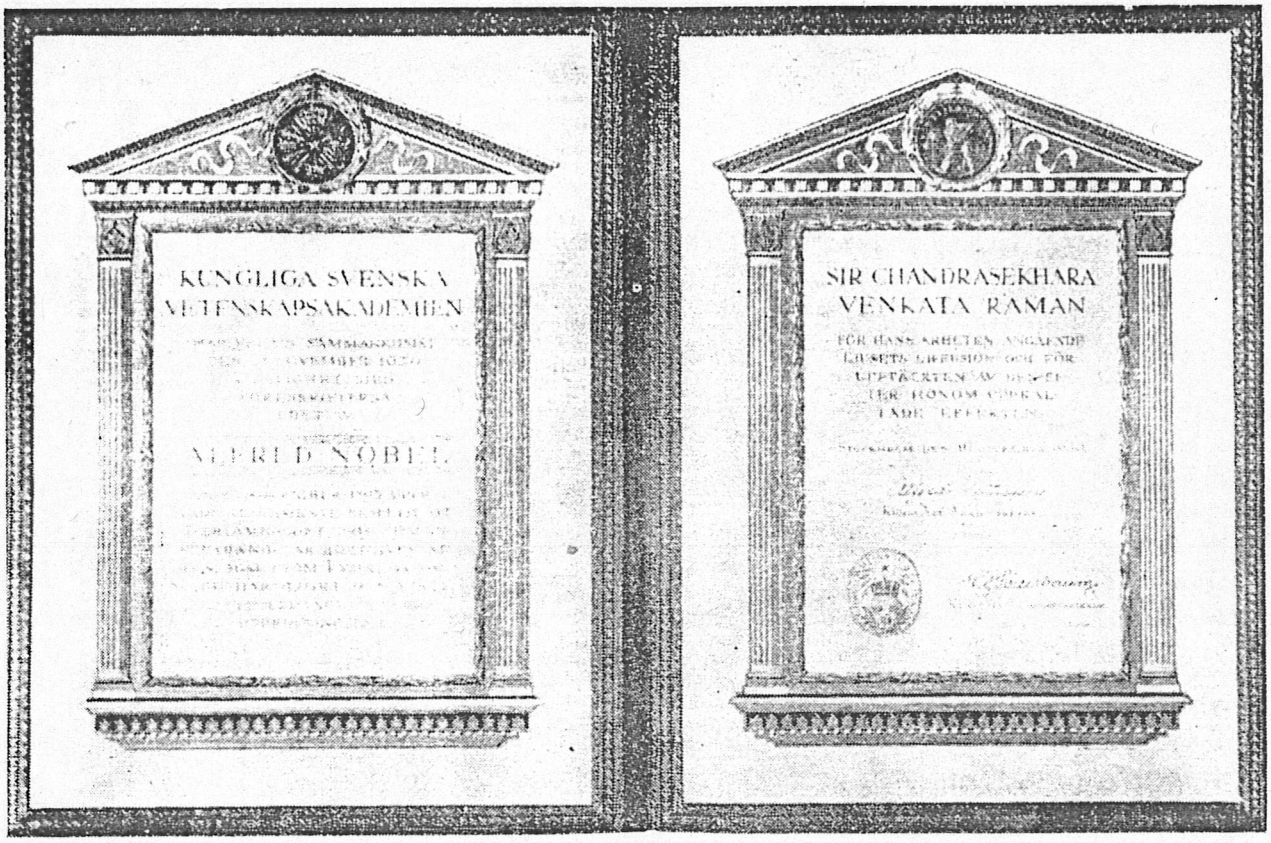


FIG: 6

The Nobel Prize Diploma.

Hand-painted and hand-lettered in Colours on vellum of very superior quality with gold embroidery on deep blue leather, the inner side of the Nobel Prize Diploma is exquisite workmanship—simple, elegant and beautiful

The whole ceremony took about 3 hours and was followed by the Nobel banquet (see bottom of Fig.7 of this article), which took place at the 'Mela', a beautiful building picturesquely situated by the side of the Malar lake. The banqueting hall can accomodate about 400 guests. The Nobel Laureates sat at the Royal Table. The dinner was of the most lavish scale. Wine flowed freely. A few vegetarian dishes

A Group of Nobel Laureates after the Ceremony

Standing from left to right: 1. Sir C.V. Raman (Physics, 1930); 2. Fischer (Chemistry, 1930); 3. Siegbahn (Physics, 1924); 4. Landsteiner (Physiology, 1930); 5. Dalen (Physics, 1912); 6. Sinclair Lewis (Literature, 1930); 7. Selma Lagerlof (Literature 1909).

The Nobel Laureates of 1930 will be seen Carrying the Nobel Diploma and Medal in their hand.

Inset—The King of Sweden

The Nobel Banquet

FIG: 7

had been considerately provided for us. When it came to the drinking of health, we had our cups fillled with water. In replying to the toast, Sir Raman spoke of the glories of ancient India. He spoke of the great renunciation of Budha, the Royal ascetic and world teacher and of his message of non-violence and love which embraced all living creation. It was nearly twelve when the party broke up.

Next day, the Nobel lectures were delivered at the University. Each prize-winner spoke on his own work. These lectures are later collected in the form of a book. In the evening, there was a reception by the King and Queen at the Palace, After dinner, the guests were shown round the library and art collections and time passed pleasantly in conversation with various members of the Royal family. We met there a grandson of Tolstoy who kindly took us to various places of interest. The 12th December was a very cold day. A chill wind was blowing. On the night we witnessed an interesting popular festival called Lucia-light. .....
Next day (14th December) we were invited to dinner at the house of the President of the Swedish Academy, Dr. Petterson. It appears that when the poet Rabindranath Tagore was there, he sang some Indian songs and the memory of it was still fresh in their minds. Some-how, they induced my husband to sing!"

9. Concluding Remarks

After return to India from the Nobel ceremony in Stockholm, Prof: Raman had to face vast crowds of admirers, anxious to see and hear the great Nobel Prize-winner. He had become so popular a figure in India that wherever he went he had often to address several meetings of citizens and students on his latest researches and on science in general. This rush of speeches and public engagements pursued him all through his long life.

On this note let me close this second article of mine on Prof: Raman, in the very fervent hope that the young men of our country will be inspired by the scenes portrayed above and to emulate his wonderful example. Let us hope that some of our brilliant young scientists will also bring the Nobel Prize in increasing number in the decades to come.

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