GANDHI MEMORIAL LECTURE SERIES

REFLECTIONS ON LIGHT

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1. Introduction

It is indeed an honour for a visitor from abroad to be invited to give a lecture in this series in which many distinguished Indian scientists have preceded me. It is my understanding that these annual lectures are dedicated to the memory of Mahatma Gandhi, whose inspired leadership was largely responsible for the creation of the independent state of India. These lectures are also dedicated to the pursuit of science in India. The name of C. V. Raman is, of course, a symbol for the numerous achievements by many Indian scientists. As a Raman Visiting Professor I hope to make a small contribution to Indian science. Since my personal scientific interests, like those of Raman, have centered for many years on the properties of light, I have chosen as the title for this talk "Reflections on Light". This title reflects immediately how our language and speech are imbued with images and concepts borrowed from the physical observation of light. The word "reflection" has acquired the meaning of "thought" as outside impressions are returned or reflected by our mental processes.

Light and colour permeate the landscape[1], our lives, and indeed the universe. The non-scientist, as well as the scientist, may be intrigued by the warming rays of the sun, the blue sky, the white, gray or black clouds, the rainbow, the sunrise, the northern lights, the glistening of wavelets on the river, the halo around the moon, the subtle colour schemes in works of art, the green forests and fields, the hues of the desert, the neon lights of the city, the reflections in the quiet lake...... The list of visual impressions and manifestations is nearly endless. Raman was much interested in the optical properties, colour and fluorescence of crystals, as well as the colours of flowers and bird's feathers. He established a fascinating collection in the Raman Research Institute here in Bangalore.

The importance of light and the sun was recognized in all early civilizations and religions. The presence of light was, however, taken for granted by the small boy who answered the question whether the sun or the moon was more important with the statement : "The moon is more important because it shines at night when light is more needed." Light is indeed necessary for life itself. The green plants utilize the sunlight to produce foodstuffs by photosynthesis, which in turn support the animal and human population on this globe.

It is no wonder that scientists through the ages have tried to understand the nature of light[2]. We know that the visual perception of light involves intricate photochemical, physiological and even psychological processes. For example, many of us have seen the sun get redder and larger as it approaches the horizon at sunset. Also, the full moon appears larger near the horizon. While the reddening has a physical explanation, the larger size is a psychological effect. When one makes an image of the sun or moon with a lens and views this image in a room, without reference to the outdoors, it turns out that the physical size of the sun or moon does not change. It is a psychological effect of perceiving relative sizes and shapes. In the same manner colour perception has many factors of nonphysical origin. We shall here restrict our attention to the physics of light, and omit the important aspects of photochemistry, photobiology and perception psychology.

Physicists have generalized the meaning of the term "light" to apply to other types of electromagnetic radiation, such as ultraviolet, x-rays and radioactive γ-rays, which are characterized by higher frequencies and shorter wavelengths than light waves. Electromagnetic waves of smaller frequencies or longer wavlengths than visible light waves include the infrared, microwave and radio waves. While these other radiations cannot be seen directly, they can be detected by other means. For example, ultraviolet and x-rays can be photographed, infrared radiation can be detected by photoconductivity, microwave and radio signals can be received with electronic equipment. All these types of radiation, if of sufficient intensity, can be perceived as heat and their energy content can be measured.

It is one of the most important aspects of experimental physics that it extends our senses a thousand, or a million or a trillionfold, and it is the marvel of theoretical physics that elegant, yet relatively simple, mathematical frameworks describe the myriad of manifestations, in particular those of electromagnetic radiation. The same mathematics may be applied to wavelengths ranging from the size of the earth, through wavelengths comparable to the diameter of a human hair, to the wavelengths of visible light which are a hundred times smaller than this, and even beyond to wavelengths smaller by another factor of a hundred million, where the dimension becomes comparable to that of nuclear particles which are one ten-thousandth of the size of an atom.

The now generally-held scientific view of the origin of the universe is the "big bang" theory[3]. Within one hundredth of a second from the beginning, the universe was filled with electromagnetic radiation (γ-rays) of incredibly high intensity, corresponding to a temperature of one hundred thousand million (10^{11}) degrees. There were roughly a billion times (10^9) more electromagnetic particles (light quanta or photons) than there were fundamental material particles (baryons). This ratio still persists today. There are many times more photons in the universe than material atoms. As the universe is ever expanding and cooling off, the remnants of the original γ-rays are now observable as the black-body microwave radiation at 3° Kelvin. This radiation was discovered as recently as 1964 by Wilson and Penzias, who shared in the 1978 Nobel prize in physics for this contribution. It is a fascinating thought that light in the generalized sense of electromagnetic radiation is indeed a prime constituent of the universe, at least as important as matter.

In this year we commemorate the 100th anniversary of the birth of Einstein, probably the greatest scientist of this century. He is reputed to have said in 1917, "For the rest of my life I will reflect on what light is," and in 1951, "All the fifty years of conscious brooding have brought me no closer to the answer of the question: What are light quanta? Of course, today every rascal thinks he knows the answer, but he is deluding himself." While ultimate understanding may escape us, one may nevertheless review the knowledge and insights gained so far, and then reconsider Einstein's remark. In the next section of this lecture I shall attempt to give an extremely condensed historical review about optics and the physical nature of light and light quanta. A few remarks about research in optics follow. The last part of this lecture contains some general comments about the relationship between optical science and society.

2. Concepts of light in history

Light was studied in antiquity ever since people bathing in the great rivers along which civilizations developed, be it the Nile, the Ganges or the Yang-tse-Kiang, saw the reflection of their own images. The Greeks and Romans used mirrors to view callers knocking on the doors of their houses. I remember from my student days in the Dutch university towns of Utrecht and Leiden that the houses along the canal were provided with mirrors, so-called "spy glasses," to watch the traffic from inside the house. I did not realize this was a 2000-year-old custom. At about 214 BC Archimedes proposed to use an array of mirrors to concentrate the sun's rays onto the sails and rigging of the enemy war vessels in the harbour of Syracuse to set them on fire.

The study of the path of light rays was closely linked to the study of geometry. Shadows indicated that light would propagate along straight lines. The law of reflection was recorded in a precise scientific statement, that the angle of incidence equals the angle of reflection, by Hero of Alexandria in the first century. The law of refraction, which describes, for example, how a stick put into the water appears to be broken, and more importantly how light rays bend through a lens or in the eyeball, was formulated about 1600 years later in

Snell's law. Eye glasses were known several centuries before that, but their use was not common, even though every older person needs glasses for reading. Even Gandhi permitted himself a pair of glasses among his scanty worldly possessions. Around the year 1600 it was still very difficult to obtain good lenses. Especially skillful artisans ground and polished glass lenses in my native country of the Netherlands. Galileo received a Dutch-made telescope which enabled him to make far-reaching discoveries about our planetary system. Van Leeuwenhoek could construct microscopes of higher magnification and resolution than anybody before him and so discovered many microscopic biological structures. It is important to note how great advances in science are closely tied to technological and experimental progress. This is as true today as was four centuries ago.

In the 17th century Newton decomposed sunlight by a prism into a coloured spectrum, and he proposed a corpuscular model of light. A light source would emit particles which would move along straight lines, as bullets from gun. It was known that light could propagate through a vacuum. as demonstrated in the laboratory by Torricelli. We now know, of course, that starlight passes through the immense distances of the much better vacuum of interstellar space. Also in the 17th century, Huyghens proposed a different model of light propagation, based on the analogy of propagation of waves in water. He applied it in considerable detail to explain the problem of birefringence in crystals, A Danish sailor had brought pieces of calcite from Greenland, and two images, instead of one, appear when an object is viewed through this transparent crystal.

During the 18th century Newton's model of light corpuscles was dominant, but the interference experiments of Young in the beginning of the 19th century could only find a natural explanation on the basis of the wave theory. Anyone who has looked at waves near the entrance of a harbour has seen how two waves may either reinforce or annihilate each other. With the subsequent theoretical developments in the 19th century by Fresnel, Maxwell, Hertz and Lorentz, the wave model became firmly established. There was much discussion of what precisely was vibrating in the vacuum. People called it the aether because of an abhorrence of empty space, but in the end aether and vacuum turned out to be one and the same. Lorentz stated very clearly that from a microscopic atomistic point of view, all electric and magnetic phenomena could be explained on a model of moving elementary charges, electrons and nuclei the constituents of matter, plus the electromagnetic fields in vacuo. The concept of wave propagation and fields avoided the notion of "action at a distance" and more importantly, provided a framework to give a consistent account of the propagation of light and electromagnetic signals.

In the beginning of the 20th century, the concept of light particles was revived by the theoretical studies of Planck and Einstein regarding the nature of black-body radiation. This is not the time nor the place to delve into the deep issues of this well-documented phase of the history of science[4,5,6]. The outcome after decades of debate is that of a dual or complementary character of wave and particle characteristics. From the point of view of an experimentalist, one should not philosophize about the nature of light in the abstract, but rather keep in mind that detectors must be used in order to find and confirm the properties of electromagnetic fields. Detectors generally consist of atoms or molecules, be they biochemical ones in the retina of the eye, or atoms with sharp spectral characteristics in a gas, or a photoelectric material surface. One says that a photon is detected when a change in the electronic configuration of the atom, retina or photoelectric cell is demonstrated. Quite generally, light is generated whenever an electron drops from an excited orbit to an orbit with lower energy in an atom or molecule. Conversely, the absorption of light raises the energy of the electron orbital, which may be observed as the impression of light by excitation of nerve cells in the retina, or as a photocurrent in a photoelectric detector. Thus, light is both created and detected by suitable interaction in material light sources and detectors. These processes are necessarily quantized because the electron orbitals are quantized. The propagation characteristics between the source and the detector (or detectors) are, however, described by waves. The intensity of the wave field at each location is a measure for the probability to detect a photon there, i.e., it is the probability that an electron orbit in the detector will be excited at that location. This duality between wave and particle aspects for light is now generally accepted, and the same duality has been adopted to describe the properties of matter. Thus, both light and matter display wave-particle aspects.

In my opinion, the explicit consideration of the sources and detectors of the light field avoids many of the conceptual difficulties which have arisen from ascribing everything to the properties of an abstract field. In particular, the wave and quantum fluctuations of black-body radiation first introduced by Einstein have played an important historical role in the development of quantum mechanics[5], but they may be understood more simply as fluctuations caused by the properties of the generation and detection process. It is also clear that the field from a chaotic source of black-body radiation has different fluctuation properties than the field emitted by a coherent laser source. The field produced by a source consisting of a single atom leads again to different field properties, which are known among specialists as photon-antibunching, rather than the more common bunching of quanta in incoherent sources with many atoms.

Einstein could, however, never accept a probabilistic interpretation of the laws of nature, and this may account for his 1951 statement quoted above. To my mind it is comforting rather than discomforting to live in a world in which probability plays an inherent role. The combination of genes that determines the genetic traits of offspring is determined by probabilities. There are important correlations, but there are also interesting variabilities. Our knowledge of atomic and molecular processes is never complete nor completely certain. The occurrence of an accident or the contraction of cancer is a matter of probability. One may adopt a life style to minimize these undesirable chances, and to maximize certain others. To my mind it would be more difficult and less interesting to live in a world where all physical events were absolutely certain.

3. Lasers and nonlinear optics

In 1960 a new type of light source was realized on earth, the laser. The word is an acronym for Light Amplification by Stimulated Emission of Radiation. It utilizes the process of stimulated emission which was postulated by Einstein in 1917, again on the basis of statistical considerations of the thermal radiation field. It is interesting how important new concepts are often discovered by routes which, with hindsight, appear quite complicated.

In a few short years the laser has become a "household" word in the English vocabulary, as well as in many other languages. A rudimentary analogy with the more familiar field of music may indicate why the laser has caused a veritable renaissance in the optical sciences[2,7]. Imagine an orchestra consisting solely of percussion instruments producing chaotic soundbursts, and imagine the change produced when string and wind instruments capable of producing pure tones are added. The light sources in pre-laser days produced a jumble of incoherent light, but the laser emits light that is characterized by a very pure frequency and very high directionality. As a consequence, its light can also be concentrated to very small spots with very high intensity.

These characteristics are used to advantage in diverse applications. To begin with a mundane example, the directionality of laser beams is used in all kinds of alignment devices by building contractors, land surveyors and mechanical engineers. Lasers are routinely used in the laying of sewer pipes, oil pipe lines and tunnel boring.

Since the laser frequency can be defined with the extraordinary precision of one tenth of one millionth of one millionth ($1:10^{13}$), the laser could be used as a time standard with a precision of one second in thirty thousand years. It can measure distances on a lathe to one hundred thousandth of an inch, and it can measure variations in distance between points on earth and the moon to within a few centimeters. So it can detect continental drifts and check relativistic corrections in satellite orbits. Small deformations in the earth's crust that might give some warning about impending earthquakes can also be detected by laser beams.

Lasers have revolutionized the science of spectroscopy, achieving orders of magnitude improvement in resolution and accuracy. Since each atomic or isotopic species has its own spectroscopic fingerprint, it is possible with laser beams to detect or isolate one particular atomic species out of billions upon billions of other atoms.

Laser beams can also be focused into glass fibers with dimensions smaller than a human hair. These fibers may be combined into cables which provide optical communication links. Such systems are already in use as links between telephone exchanges in several metropolitan cities. The field of communications and information processing, revolutionized by the transistor and large scale integrated circuits, will be changed further by techniques of optical electronics, laser scanning and printing.

High power laser beams are used in the automotive industry to weld steel plates and to apply surface heat treatment to complex engine parts. Laser beams of modest power are used to cut emery paper, drill holes in diamond, or cut cloth rapidly and precisely. The laser beam can be steered faster and more accurately by electronic means than mechanical cutters. In the case of synthetic fibers no finishing of the edges is necessary, as the fibers are sealed by the heat at the laser focal spot.

The laser as a fine cutting and heating tool is finding increasing applications in medicine. Detached retina welding operations are routinely performed with lasers. Microsurgery of vocal cords and other delicate operations may be performed by the laser spot scalpel. Cut blood vessels are automatically cauterized, avoiding the need for clamps and stitches. Laser light may be used in the interior of the body via optical fibers.

The high intensity available in focused and pulsed laser beams has also led to the development of a new branch of optics. It is called nonlinear optics because at high intensity the graph representing the dependence of the optical polarization on the light field amplitude has curvature and deviates from a straight line. Again an analogy with the acoustics of musical instruments may be helpful. When a string is bowed with much force or a wind instrument is blown hard, many harmonic overtones may be generated. A similiar thing happens to the electrons in matter when they are violently excited by a high intensity light beam. Overtones of light are created. This has the dramatic effect that a red light beam may be changed to an ultraviolet beam with twice or three times the frequency, or one-half or one-third of the wavelength. Basic laws of optics are modified in the nonlinear regime. It is possible for the reflected ultraviolet ray, created by a high intensity red beam incident on a mirror consisting of a nonlinear material, to come back in a different direction from the red reflected ray which follows the millenia-old law that the angles of incidence and reflection are equal.

Another common notion that light rays can cross each other in a transparent medium, such as the air in this room, without interaction or hindrance, must be abandoned in the nonlinear regime. Interactions between different light waves do occur. In the process the colour or the frequency of the light beams may change. These nonlinear characteristics are also essential in light communications systems.

There is a close relationship between some of these nonlinear effects and the frequency change observed by Professor Raman in the scattering of light from molecules and crystals. The effect which bears his name has a nonlinear or stimulated counterpart which has extended the possibilities of Raman-type spectroscopy.

4. Optical science and society

This brief historical flight over optics research may have presented the non-scientists in the audience with a bewildering array of scientfic details, but I hope to have convinced most of you that the study of light has had an influence on society through the ages, both in an abstract ideological and in a practical technological sense. It should also be clear that progress was made in a succession of steps taken by individual scientists. Even in the present era of scientific teamwork, optics is still "small science", and successful research can be accomplished by individuals with relatively modest apparatus. The sense of individual freedom to penetrate beyond the frontiers of existing knowledge is as fascinating for the scientist today as it was several centuries or several millenia ago. It may be compared with the scaling of an uncharted summit by a mountaineer.

The individual freedom of the scientist, as that of the mountaineer, is not circumscribed by man-made laws but rather by the laws of nature. It is in this latter sense that one must understand the words of the German poet Goethe, who, parenthetically, also wrote a book on the science of colours, "Unbridled minds will seek in vain the peak of perfection; within boundaries becomes mastery evident, and only the law can give us freedom." It is a matter of record[8] that Gandhi was influenced by the writings of Thoreau, the American philosopher and naturalist. Thoreau had advocated opposition and nonviolent disobedience to man-made laws if these were in conflict with more universal concepts of social justice or natural laws.

Today scientists usually do not have to face prison or burn on the stake if they hold forth unpopular views, as was still true in Galileo's time. The esteem for individual freedom, the questioning of widely-held conventional beliefs and, if necessary, the challenging of authority all provide a link between scientists, Thoreau and Gandhi, although the moral and physical courage of the latter is, of course, hard to match. Personal freedom is respected in India, and its science and scientists are respected at the international level. It is interesting to compare the status of science in the two most populous nations, India and China. The cultural revolution in China tried to wipe out all traces of an intellectual elite. As a consequence, its science has a long, arduous road ahead to catch up with the international scientific communtiy. A start has been made following a radical change in Chinese science policy after Mao's death.

A few of the greatest scientists have occasionally been carried away by the sheer beauty of their intellectual creations and overstepped the natural laws. A fascinating account of this has recently been given by that great theoretical astrophysicist of Indian descent, S. Chandrasekhar.[9] He analyzes the quest for beauty in scientific theories. Sometimes the beauty and harmony of unexpected proportions and relationships in a newly-discovered theoretical framework become so overpowering that the artist-scientist-creator succumbs to the notion that he has found the absolute truth. Over-confidence in judgment is evident in the following statement attributed to Einstein: "When judging a physical theory, I ask myself whether I would have made the universe in that way, had I been God." Einstein would not admit the existence of the probability concept in a definitive theory. This explains his view that nobody understands the nature of light quanta.

The laws of science, however, are not solely the product of theoretical speculation, but there is a continuous interplay with experiment. Sometimes the experiments are designed to check a theoretical idea; at other times unexpected experimental observations and discoveries lead to new theoretical concepts.

Respect for the facts, for the realities imposed by matter, and adjustment to the frustrations of equipment and instruments that hardly ever perform perfectly, are among the most valuable lessons of scientific research. Experimenters may not soar to the same Olympian heights as the great theorists, but they also have less chance to attach more weight to their own inventions than to the laws of nature. Each scientist at his own level participates in an aesthetic experience, which may include, separately or jointly, design of instrumentation, observation of new phenomena, finding fits between existing theory and experiment, or the creation of new mathematical structures.

Many scientists also get considerable satisfaction from teaching, presenting and communicating the scientific and technological knowledge to others.

It seems to me that here another parallel may be drawn with Gandhi's life. His accomplishments are so great because he not only had a vision of social justice but he also adapted his life style so that he could teach and communicate with the poor masses. He made a connection between social justice and social realities.

We would delude ourselves if we ignored the enormous separation between scientists and the masses that are too hungry and too tired to think. While many scientists obtain a considerable degree of motivation in their work from its technological relevance, the benefits of high technology to third world countries are often small or even negative. The problems of the poor and illiterate masses of humanity are clearly not going to be solved by research in physics. Another cautionary note is struck by the observation that most advances in science and technology may be used with equal success for peace as for war. We mentioned the use of light as a weapon at the battle of Syracuse more than 2000 years ago, and we know that laser weapons have been deployed during the past decade. Some of this weaponry is defensive, some offensive; some is stabilizing the balance of power, some is not. These aspects may not be ignored, but neither should they be used as an excuse to discourage laser research and to prevent progress in medicine, communications and other peaceful pursuits.

In particular, improved communications among individuals and between nations of this world appear vital. Communication is also a precondition for education. Light has been used to communicate since the early American Indian produced smoke signals by uncovering or covering his fire with a blanket, and since the ships on the Mediterranean were guided by light towers. Modern optics will contribute to the means of high capacity information and communication channels, which may be useful also in third world countries to reach the masses. They can, however, not replace the pyramid of education that should extend from the highest institutes of research through intermediate levels of universities and colleges, down to high schools in the cities and on to grade schools in every village. Adult education opportunities should be available at all these levels, as well. It clearly requires a dedicated army of teachers at all levels, and it will take more than one generation to learn that some deep-rooted social customs and religious beliefs require change. They were established at times before the life expectancy for individuals was increased enormously due to inprovements in public health and medicine, and before mechanical labour could be performed more efficiently than by human muscle power.

One of the most widely held human beliefs is the idea that happiness, progress and security require the production of a maximum number of sons. This idea, whose time is definitely past, is still actively promoted by religious prelates who want more souls, generals who want more soldiers, political leaders who want more votes and landowners who want more cheap labour. They all appear to be more concerned with quantity than quality, because uneducated masses can be kept captive. Many different cultures, religions and nations still cultivate this notion about the blessing of procreation and exponential growth in numbers. It is especially strong in that great arc that stretches from Southeast Asia, through the Indian subcontinent, the Middle East, the Mediterranean and across the Atlantic to Latin America.

The only hope to check rampant population growth lies in massive educational programs. It is especially important that women participate in this educational process at all levels. I am grateful to my wife for having taught me this lesson. The human race has the capacity to learn and to adapt. So, new views on procreation may spread as fast in the next decades as the populations have in the decades just past. Since the earth is finite, the source of materials and fossil fuels is exhaustible, the cultivated land areas cannot be increased very much, the supply of fresh water is limited and the capacity of the atmosphere to absorb waste products also has its bounds ; therefore the quality of human life can increase only by a decrease in quantity. Key elements to soften the impact of the inexorable laws of conservation of energy and matter on the future of man- and womankind appear to lie in education and communication. For a final observation on these two subjects, I should like to return momentarily to the concept of the light quantum which acquires a precise meaning only if considered in combination with its source and its detector. In a similar manner, truth is not absolute but is in need of at least two persons : "One to speak it, and one to hear it." This final quotation is Thoreau's.

References

1. M. Minnaert, *Light and Colour in the Open Air*, G. Bell and Sons, London, 1940 (translated from the Dutch, Theime, Zutphen, 1937).

2. See, for example, *Lasers and Light*, ed. by A.L. Schawlow, readings from the Scientific American, W.H. Freeman and Co., San Francisco, 1969.

3. Steven Weinberg, *The First Three Minutes*, Basic Books, Inc., New York, 1977.

4. See, for example, E. Wolf, Einstein's researches on the nature of light, Optics News, Optical Society of America, Winter 1979, p. 24.

5. M. J. Klein, *The Natural Philosopher*, Blaisdell, New York, Vol. 2, p. 57, 1963, and Vol. 3, p. 1, 1964.

6. A. Pais, Reviews of Modern Physics, **51**, October 1979 (in press).

7. N. Bloembergen, Lasers, a renaissance in optics research, American Scientist, **63**, 16, 1975.

8. L. Fisher, *Gandhi*, Mentor, The New American Library, Inc., New York, 1954.

9. S. Chandrasekhar, Beauty and the quest for beauty in science, Physics Today, p. 25, July 1979.