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1971 Low-key crystallography. *Am. Mineral.* **56,** 375–386.

1972 (with L. S. Land, and E. Mutis) Crystallochemical and geochemical comparisons of recent and older dolomites. *7th Forum on Geology of Industrial Minerals, Florida Bur. Geol., Spec. Publ.* **17.**

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Memorial of Sir (William) Lawrence Bragg
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PETER GAY

Department of Mineralogy and Petrology,
University of Cambridge, England

Of very few men can it be said that they played the major part in founding a new branch of science, but since Sir Lawrence Bragg achieved this distinction at the outset of his career he had the unique satisfaction of witnessing the impact of X-ray analysis upon the studies of matter from the simplest ionic compounds and metals through the increasing complexities of minerals to the immense molecules of the living cell. Not that he was a bystander only, for his scientific curiosity led him to make major contributions in most of these fields. He recognized the importance of a personal involvement in the development of ideas and wrote that ". . . science is unlike the arts, where the value of original thought is often enhanced by time. Science is like a coral reef, alive only on the growing surface." This philosophy stimulated him throughout his life.

Bragg was born in Adelaide, South Australia, five years before Röntgen discovered X-rays, and was reading physics at Cambridge when the diffraction of X-rays by zincblende was first demonstrated in Germany early in 1912. He heard about these experiments from his father Sir William Bragg, then Professor of Physics at Leeds, during the summer of that year, and immediately began to re-interpret the patterns so as to eliminate some of the apparent discrepancies in von Laue's original approach through three-dimensional scattering. Within a very short time he told the Cambridge Philosophical Society how the diffraction effects could be completely and simply explained in terms of "reflexions" from successive atomic planes in the structure and he rewrote the diffraction conditions of von Laue in the form that succeeding generations of crystallographers have come to know as Bragg's Law. This imaginative intellectual leap by a twenty-two year old student displayed an uncanny insight into the description of natural phenomena, a quality to become apparent throughout his scientific work. With his father he developed an X-ray spectrometer which was used to solve the structures of rocksalt, diamond, fluorspar, pyrites, calcite, cuprite, corundum, and metallic copper; for this work the Braggs were jointly awarded the Nobel Prize for Physics in 1915. But their researches were interrupted by the First World War in which Sir Lawrence served with the cavalry; he devised a sound ranging method for the location of enemy artillery and was decorated with the Military Cross in 1918.

Resuming his scientific career after the war, he became Professor of Physics at Manchester in 1919, a post which he was to hold until 1937. In this period came the first generation of pupils and collaborators, who, in Manchester and elsewhere in Britain and overseas, were to build upon the foundation laid down by the Braggs; the list of publications from his department at Manchester in the inter-war years reveals names such as R. W. James, D. R. Hartree, C. G. Darwin, A. J. Bradley, W. H. Taylor, B. E. Warren, W. H. Zachariasen, T. Ito, and many others familiar as substantial contributors to the development of modern crystallography. With his co-workers Bragg advanced understanding of the factors which affect the intensities of X-ray maxima and how such knowledge could be applied to the determination of more and more complex structures. Inevitably this led him into silicate mineralogy, where apparent chaos in the chemistry was waiting to be rationalized. He summarized this work in a book *Atomic Structures of Minerals* written during a period as a visiting professor at Cornell in 1934, a remarkable achievement for a man who declared in the preface "It will be clear to mineralogists who read these pages that the author knows very little of their subject." Bragg echoed this sentiment in accepting the Roebling Medal in 1949 when he described how on another occasion he had shocked a mineralogical audience by opening a lecture with the statement that "there are only six minerals in the earth's crust if one neglects some tiresome details." Modern mineralogy is founded on the work of structural crystallographers, among whom Bragg was pre-eminent, and we must be grateful that he was stimulated by the challenge. Towards the end of his Manchester period, his interest turned to metals, a field in which he remained active during his short stay as Director of the National Physical Laboratory in 1937–38 and for the first ten or so years of his appointment as Cavendish Professor of Experimental Physics in Cambridge which he took up in 1939. He was stimulated by the results of alloy structure analyses and behavior, and this resulted (in collaboration with E. J. Williams) in models for order-disorder phenomena then becoming apparent. Latterly Bragg turned to plastic flow and deformation, and perhaps it is in this field that his personal contribution is least obvious in the literature (though the use of bubble models to illustrate intercrystalline boundaries and plastic flow stands as another example of his illustrative insight). But if his name is not one immediately associated with metal physics, his indirect influence upon those working upon these problems was significant. It was at this time that I first met him as part of a team wrestling with the new technologies involved in developing microbeam cameras and high-intensity X-ray sources which we were to use to look at the fine structure of deformed metal crystals; Bragg's transparent, almost boyish, enthusiasm for the potentialities of a new tool helped to sustain us through the many dark days of a prolonged development period.

It was at Cambridge, too, that Sir Lawrence turned to his ultimate scientific quest, the crystallographic study of proteins and what has now developed into molecular biology. Throughout his career, he had never lost his interest in the determination of more and more complex structures, and even when engaged in other fields had continued to seek improvements in the methods of structure analysis; in 1939 he devised an X-ray microscope (an optical method for the summation of two dimensional Fourier series), and in 1945 he set up the "fly's eye" apparatus (another optical aid to structure determination) to provide a foundation for the optical analogues which were developed by others later. Against such a background it was natural that he should respond to the challenge of the complex molecules to be found in living cells. In the metal physics group in the late forties we noticed that our talks with Bragg were becoming less frequent and that when they took place they often concluded with his telling us about the progress of work on haemoglobin. Studies in this field had been going on in the Cavendish Laboratory since the mid-thirties, but when Bernal left shortly before the war they had been carried on almost alone by Perutz. Funds for this research were rapidly dwindling in 1947 when Bragg persuaded the Medical Research Council to set up a Research Unit in the Cavendish; it was as part of this Unit that Perutz and Kendrew, and later Crick and Watson, carried out Nobel Prize winning work, and the Unit eventually matured into the Medical Research Council Laboratory of Molecular Biology quite independent of the Cavendish. By this time Bragg had made his final move, for in 1953 he left Cambridge to become Fullerian Professor of Chemistry at the Royal Institution in London, assuming responsibility as Director a year later, a post which he held until his retirement in 1966. For these last years in London he pursued his interests in protein crystallography as leader of a new small group that he assembled, and also found time to revise (with G. F. Claringbull) his earlier structural book on minerals republished as *Crystal Structures of Minerals* in 1965. Over the last twenty years of his life, he also became increasingly interested in the teaching and popularization of science, a task for which his gifts of lucidity and simplicity of expression made him admirably suited. His vacation lectures at the Royal Institution, attended by over twenty thousand school children each year, presented the fundamentals of optics, electricity, and magnetism in such a way as to involve his audience with his own enthusiasm for natural phenomena; he also gave a highly successful series of television broadcasts on the properties of matter that brought him still wider recognition. In these activities the elegant demonstrations that he devised, his skill in presentation, and his considerable personal charm combined to make him one of the best illustrators of science and its methods in living memory.

In such a long and distinguished life, honours were showered upon Bragg. An FRS in 1921 was followed by honorary degrees and membership of learned societies around the world; on different occasions he was awarded the Hughes, Royal, and Copley Medals by the Royal Society. Among more public recognitions, he was knighted in 1941 and made a Companion of Honour (a rare distinction for a scientist) in 1967. But all this had no effect upon the essential man; his ambitions were not for himself but for the science which he helped to found. In a fascinating, but unpublished, brief commentary on his own publications, his comments reinforce this conviction; for example, writing about his papers with Perutz on the structure of haemoglobin and their effect upon final solutions for protein molecules, Bragg says: "My part in all this, I think, was to keep them encouraged and help to glean small bits of the solution which kept us all keen until eventually the final answer came out."

Whilst he maintained his progressive scientific curiosity throughout his life, at the personal level he remained an Edwardian with many of the customs and attitudes of his early, formative years. He enjoyed formality whether at Cambridge College Feasts or more grand occasions, and there was always a reserve between Bragg and his most intimate scientific collaborators. His family life was separated from his scientific work, and Lady Alice (whom he married in 1921) was known to many of Bragg's colleagues only through her many public works. The Braggs had two sons and two daughters, and in his later years Sir Lawrence enjoyed the company of his grandchildren, who acted as models for portraits in crayon or chalk. Indeed sketching and painting, together with bird-watching and gardening, were his main recreations, and it has been said that it was this artistic perception that led to the originality of his scientific ideas. Certainly he often summarized his conclusions in sketches, and he leaned towards the use of models rather than rigorous mathematical methods; symbols did not attract him, and he could not remember chemical formulae of silicates or amino-acids. But this illustrative talent was only one facet of the formidable intellect behind the genial facade, and perhaps his greatest gifts lay in his astute penetration to an underlying simplicity and his sound scientific judgment which allowed him to assess the validity of a solution almost instinctively. "I am sure this is how it must work" was a characteristic phrase which commanded respect from any scientist.

His lasting memorial (and one in which he would take great pride) lies in the crystallographic schools around the world started and continued by generations of pupils of Sir Lawrence and his father. Some of us in the second generation had the privilege of working in a laboratory headed by Sir Lawrence Bragg and we all remember him with affection and respect. We know already that he was one of the great men of science of the twentieth century, and we are convinced that future historians of science can only confirm our opinion.

Selected Publications of Sir Lawrence Bragg

In such a long and distinguished career, a complete bibliography would contain many contributions to journals around the world at different levels of scientific and general interest; over 180 publications have been traced but it is by no means certain whether such a list is exhaustive. An arbitrary and personal selection of his publications is given below chosen to illustrate the progression of Bragg's scientific interests that has been outlined in this memorial and his more important contributions to each field.

1913 The diffraction of short electromagnetic waves by a crystal. *Proc. Camb. Phil. Soc.* **17,** 43–57.

The structure of some crystals as indicated by their diffraction of X-rays. *Proc. Roy. Soc.* **A89,** 248–277.

1914 The analysis of crystals by the X-ray spectrometer. *Proc. Roy. Soc.* **A89,** 468–489.

1921 (with R. W. James, and C. H. Bosanquet) The intensity of reflexion of X-rays by rock-salt. *Phil. Mag.* **41,** 309–337; **42,** 1–17.

1924 The refractive indices of calcite and aragonite. *Proc. Roy. Soc.* **A105,** 370–386.

The influence of atomic arrangement on refractive index. *Proc. Roy. Soc.* **A106,** 346–368.

1926 (with C. G. Darwin, and R. W. James) The intensity of reflexion of X-rays by crystals. *Phil. Mag.* **1,** 897–922.

1929 The determination of parameters in crystal structures by means of Fourier series. *Proc. Roy. Soc.* **A123,** 537–559.

1930 The structure of silicates. *Z. Kristallogr.* **74,** 237–305.

1933 *The Crystalline State,* Vol. 1, *A General Survey.* Bell, London.

1934 (with E. J. Williams) The effect of thermal agitation on atomic arrangement in alloys. *Proc. Roy Soc.* **A145,** 699–730.

1935 (with E. J. Williams) The effect of thermal agitation on atomic arrangement in alloys. II. *Proc. Roy. Soc.* **A151,** 540–566.

1937 *Atomic Structure of Minerals.* Cornell University Press.

1939 A new type of X-ray microscope. *Nature,* **143,** 678.

1940 The structure of a cold-worked metal. *Proc. Phys. Soc.* **52,** 105–109.

1945 (with A. R. Stokes) X-ray analysis with the aid of the "fly's-eye". *Nature,* **156,** 332–333.

1947 (with J. F. Nye) A dynamical model of a crystal structure. *Proc. Roy. Soc.* **A190,** 474–481.

1949 (with W. M. Lomer) A dynamical model of a crystal structure. II. *Proc. Roy. Soc.* **A196,** 171–181.

Giant molecules. *Nature,* **164,** 7–10.

The strength of metals. *Proc. Camb. Phil. Soc.* **45,** 125–130.

1952 (with M. F. Perutz) The structure of haemoglobin. *Proc. Roy. Soc.* **A213,** 425–435.

1954 (with E. R. Howells, and M. F. Perutz) The structure of haemoglobin. II. *Proc. Roy. Soc.* **A222,** 33–44.

1958 The determination of the co-ordinates of heavy atoms in protein crystals. *Acta Crystallogr.* **11,** 70–75.

1965 First stages in the X-ray analysis of proteins. *Rep. Prog. Phys.* **28,** 1–14.

(with G. F. Claringbull) *The Crystalline State.* Vol. 4, *Crystal Structures of Minerals.* Bell, London.

1966 The art of talking about science. *Science,* **154,** 1613–1616.

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Memorial of Kent Combs Brannock
July 20, 1923—February 21, 1973

JOHN S. WHITE, JR.

National Museum of Natural History, Smithsonian Institution, Washington, D. C. 20560

Kent Combs Brannock was one of a relatively small number of modern vintage "amateur" mineralogists with sufficiently high levels of technical competence and constant interest to give him a professional's understanding of mineralogy. His love of minerals was contagious, and was a continuing source of inspiration to those around him less dedicated than he to their collection and study. The amateur group lost one of their most outstanding members when "Casey," as he was known to his friends, passed away on February 21, 1973, at the age of 49, in Kingsport, Tennessee.