2014 INTERNATIONAL YEAR OF CRYSTALLOGRAPHY: BIRTH AND IMPACT OF X-RAY CRYSTALLOGRAPHY

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The United Nations have declared 2014 International Year of Crystallography to commemorate the 100th anniversary of the award of the Nobel Prize to Max von Laue for his discovery of X-ray diffraction by crystals. Following this important recognition the International Union of Crystallography, together with UNESCO, has launched an intense program of events and initiatives all over the world to promote the knowledge and image of this important science, not only within the scientific community, but also with the general public. I am therefore grateful to the Società Italiana di Fisica for offering this opportunity to present a historical account of the early steps of X-ray crystallography and of the impact of this discovery on several other branches of science*.

1 Introduction

Crystals have always attracted our attention for their regular and beautiful shapes, which have been studied since ancient times by Plato, Aristotle, Pliny the Elder and others. Morphological crystallography developed from a simple classification of the shapes of minerals to the attempt to explain their regular forms in terms of the arrangement of the elementary constituents, which led Haüy to propose a three-dimensional periodic arrangement (fig. 1), paving the road to the modern concept of space lattice. The discovery that crystal lattices diffracted X-rays marked the advent of modern crystallography with a great forward leap in the understanding of their structure.

The very beginning was in 1895, when Roentgen (fig. 2), while carrying out some experiments on cathode rays, discovered a mysterious and penetrating radiation and called it X-rays. The news had a great echo, not only for the possible

* For a detailed account the reader is referred to the recent book on the Early Days of X-ray Crystallography by A. Authier [1], where a complete list of references of scientific papers and books is provided.

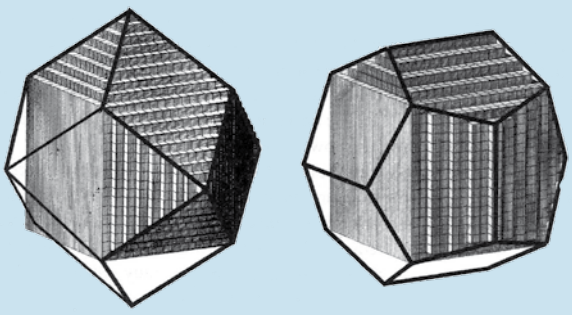

Fig. 1 Haüy description, through decrements along the edges of periodic patterns, of rhomb-dodecahedron and pentagon-dodecahedron.

Fig. 2 W. C. Roentgen.

Fig. 3 M. von Laue.

Fig. 4 P. P. Ewald.

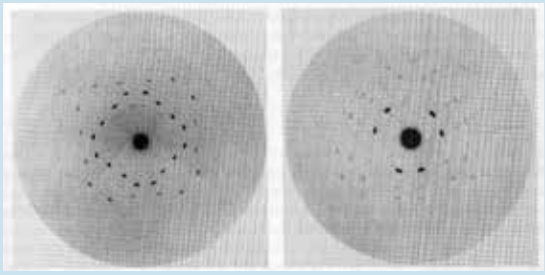

Fig. 5 X-ray Laue diffraction patterns of zinc-blend crystals obtained by Friedrich and Knipping.

medical applications, but also because X-rays attracted the attention of many physicists, such as J.J. Thomson and Lord Kelvin, who tried to explain their nature. Roentgen was awarded the first Nobel Prize in Physics in 1901. The discovery initiated a long and animated discussion over the corpuscular or wave nature of X-rays, that led Sir W.H. Bragg to exclaim: "On Mondays, Wednesdays, and Fridays we use the wave theory; on Tuesdays, Thursdays, and Saturdays we think in streams of flying energy quanta or corpuscles". In 1901 Sommerfeld derived for X-rays a width of pulse of the order of 1.0 Å and later in 1905 he wrote: "It is a shame that, ten years after Roentgen's discovery, one still does not know what Roentgen rays really are".

2 The discovery of X-ray diffraction and its impact and developments

It is certainly not accidental that the discovery of X-ray diffraction by crystals in 1912 occurred in the culturally exciting scientific milieu of Munich. The scenario of the discovery in the three main scientific institutions: Institute for Mineralogy and Mineral Sites directed by Groth, Institute of Experimental Physics directed by Roentgen and Institute of Theoretical Physics directed by Sommerfeld, was the unifying pot of the knowledge on the lattice nature of crystals and of the theoretical and experimental physical bases that allowed to think of and realise such an innovative experiment. Laue (fig. 3) did his doctoral work with Max Planck and in 1909 went to Munich as Privatdozent in Sommerfeld's Institute, where Paul Ewald (fig. 4) was working at his doctorate thesis. Ewald sought Laue's help and asked him some questions on the dispersion of light by a regular array of resonators (a model for a crystal). Ewald's intelligent questions triggered Laue's intuition that X-rays could be diffracted by crystals, which was immediately confirmed by Friedrich and Knipping's first diffraction experiments (fig. 5).

The news of the discovery quickly propagated and stimulated a strong reaction, and soon reached W. H. Bragg (father) (fig. 6, left), who favoured a "corpuscular" interpretation of X-rays and his son W. L. Bragg (fig. 6, right), who in 1913 was a PhD student in Cambridge when, assuming a wave nature of X-rays, derived his famous law ($n\lambda = 2d \sin\theta$) interpreting diffraction by crystals as in-phase reflexion by lattice planes.

Together the Braggs initiated the era of crystal structure determination and were awarded the Nobel Prize in Physics in 1915, but because of the war, W. L. Bragg could only deliver the Nobel Lecture in 1922. The reading of this lecture is fascinating as you are taken through the simultaneous interpretation of both X-ray spectra and crystal structures (with almost no information on atomic structure and dimensions), using the X-ray ionization spectrometer (fig. 7), the ancestor of modern diffractometers. "In this instrument the X-rays coming from a tube are limited to a narrow beam by slits, and fall on a crystal at the centre of the spectrometer table by which they are reflected; the reflected beam is received and measured in an ionisation chamber". The first crystal structures of alkali halides and diamond were determined and were soon followed by other simple inorganic compounds. The discussion about the nature of X-rays and the interpretation of the diffraction process went on and the first high-frequency spectra of the elements allowed H.G.J. Mosley to formulate his law [$\nu = \nu_o A(Z-b)^2$] relating the frequencies of the spectra to the atomic number and predict some missing elements in the Periodic Table.

It can be shown that the electron density function (*i.e.* the structure) in a crystal is the Fourier transform of the diffracted amplitudes, which are complex quantities defined in modulus

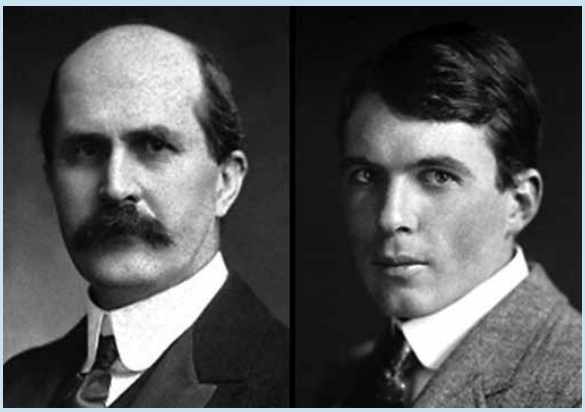

Fig. 6 W. H. Bragg (father) and W. L. Bragg (son).

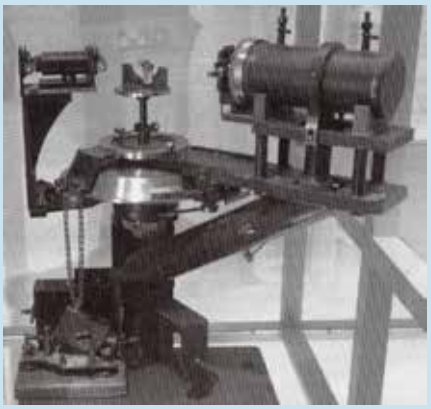

Fig. 7 X-ray ionization spectrometer built by W. H. Bragg.

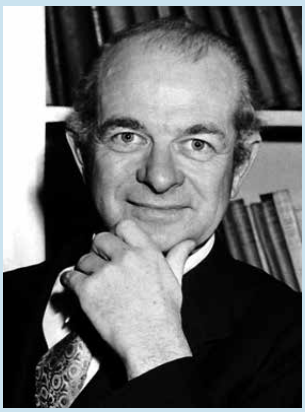

Fig. 8 L. Pauling.

and phase. Diffraction experiments can only give the moduli and structure determination requires the solution of the "phase problem". Before 1925 only fairly simple inorganic structures could be solved by intelligent trial and error guesses, with the aid of space-group symmetry. Besides Laue and rotating crystal photographs and spectrometer recordings, also diffraction by crystalline powders was introduced and used. The introduction of Fourier methods and the use of the Patterson function permitted the solution of a number of rather complex inorganic structures. The structure of diamond had already shown the tetrahedral arrangement of the four carbon atoms around each carbon atom in the crystal, thus suggesting the same geometry for methane and all saturated aliphatic hydrocarbons, while the solution in 1928 by K. Lonsdale of one of the first organic structures, hexamethylbenzene, modified Kekulé's picture of alternating single and double bonds in benzene.

At the same time some insight into the intensity of diffracted X-rays, the factors affecting intensities, the integrated intensity, the atomic scattering factor and the electron density was acquired. Improved powder diffraction cameras, rotating and oscillating crystal methods and Weissenberg camera to explore the reciprocal lattice (representing the diffraction pattern) became available, and a better understanding of the theory of absolute intensities and extinction and of the role of crystal perfection and crystal defects in the diffraction process was gained.

2.1 Applications in different fields

In the following years X-ray diffraction allowed the investigation of the structure of matter in the solid state and gave a major contribution to the understanding of the nature of the chemical bonds, allowing Linus C. Pauling (fig. 8) to open the new science of *Structural Chemistry*. Polar and non polar bonds in inorganic crystals were analyzed and ionic and atomic radii measured. The study of solid solutions allowed Vegard to formulate his law relating cell parameters to composition; Goldschmidt, from the analysis of several classes of compounds, proposed a classification and introduced the concept of *coordination number*; Pauling proposed a set of rules governing the structure of inorganic crystals and introduced the idea of *coordination polyhedral*, and was awarded the 1954 Nobel Prize in Chemistry "for his research into the nature of the chemical bond and its application to the elucidation of the structure of complex substances". The same Prize was conferred on W.N. Lipscomb in 1976 "for his studies on the structure of boranes illuminating problems of chemical bonding". The more recent growth of structural information required the setting up of the Inorganic Crystal Structure Database (ICSD), which now contains over 140000 structures.

Organic crystals showed the presence of molecular crystals and gave insight into the nature of covalent bonds and of intermolecular interactions and into the stereochemical properties of molecules. More recently, thanks to the advent of more powerful computers allowing structure solution by the so-called Direct Methods (H. A. Hauptman and J. Karle received the 1985 Nobel Prize in Chemistry "for their outstanding achievements in the development of direct methods for the determination of crystal structures"), a large number of organic and metallo-organic crystal structures could be solved and the information was collected in the Cambridge Structural Database. Today the database holds more than half a million entries and is a basic instrument for systematic studies on structure correlation, intermolecular interactions, conformational analysis and combined crystallographic/quantum-mechanical studies. The analysis of the crystal structures of compounds belonging to relevant classes allowed

Fig. 9 D. Shechtman.

Fig. 10 Artistic periodic patterns at the Alhambra in Granada (left) and painted by Escher (right).

Jean-Marie Lehn, D. J. Cram, and C. J. Pedersen to formulate the concept of *Supramolecular Chemistry* and for this they were awarded the 1987 Nobel Prize in Chemistry "for their development and use of molecules with structure-specific interactions of high selectivity". We should also mention the 1996 Nobel Prize in Chemistry to R. F. Curl, H. W. Kroto and R. E. Smalley "for their discovery of fullerenes" a new form of carbon.

The study of metals and alloys not only allowed to define the way in which atoms are held together, but also to obtain clearer and more complete phase diagrams, to gain insight on order-disorder transitions and on the properties of intermetallic compounds, and to study the effects of imperfections and mutual orientation of the crystalline grains on the properties of metallic compounds. It was in this field that the concept of quasicrystal (a non-periodic ordered crystal) originated in 1982, when Dan Shechtman (fig. 9), studying an Al-Mn alloy, observed a diffraction pattern with a "forbidden" 10-fold symmetry. The theoretical and practical relevance of this discovery was recognized by the award of the 2011 Nobel Prize in Chemistry to Shechtman "for the discovery of quasicrystals".

Up to 1912 Crystallography was a branch of mineralogy, but the study of minerals by X-ray diffraction opened the new rich field of *Structural Mineralogy*. Examples of the major outcomes of these studies are the structural classification of silicates and the systematic study of rock-forming minerals.

The study of lattice geometry and of the symmetry rules governing the close packing of objects in one, two, three and higher dimensions is the field of mathematical investigations, which have found important practical applications not only within *Mathematical Crystallography*. A side aspect of these studies is their relations with artistic creations in which repeating patterns and symmetry, that have always been the fascinating features of crystals, were used in a superb way, as in the cases of the Alhambra mosaics and Escher pictures (fig. 10) and many other masterpieces.

Since many physical properties of crystals depend on their structure, diffraction studies are essential in materials science, where the possibility of appropriate atom exchanges in the structure can be used to modulate the properties of materials. For instance the exchange of Si atoms with other appropriate atoms, such as Al, Fe, Ti, B, in the silica cage framework of zeolites is used to obtain specific catalytic properties. The structural features of catalysts and of synthetic polymers can be related to their specific properties.

The structural interpretation of physical properties is an important goal of *Crystal Physics*. Three early examples are the zero-point energy, piezoelectricity and phase transformations. Crystal imperfections and their effects were also investigated. Today crystal physics studies the optical properties of crystals, their elastic and thermal and in general all tensor properties, which are at the basis of some relevant applications. An important event was the 1987 Nobel Prize in Physics to J.G. Bednorz and K.A. Müller "for their important break-through in the discovery of superconductivity in ceramic materials".

A relevant research activity, naturally related to crystallography, is *Crystal Growth,* which, because of its importance for modern applied technologies (electronic devices, optoelectronic, gemmology, etc.), has seen a large development, also in several industrial laboratories, both in its fundamental aspects and in its applications.

The first structural studies of biological substances were carried out on natural fibres such as silk, wool, cellulose, etc. especially by Atsbury, who is considered the father of

Fig. 11 The Nobel Prize winners in 1962: from left M. Wilkins, M. Perutz, F. H. C. Crick, J. Steinbeck, J. D. Watson, and J. Kendrew.

molecular biology. The most famous work based on the interpretation of a fibre diffraction pattern was that on the structure of DNA by F. H. C. Crick, J. D. Watson, M. Wilkins and R. Franklin. The first paper was published by Watson and Crick [2], who, together with M. Wilkins were awarded the Nobel Prize in Medicine in 1962 (fig. 11). The essential contribution of Rosalind Franklin (fig. 12) could not be recognized because of her death in 1958 at the age of 37 and the story of DNA turned out to be a tale of competition and intrigue, told from different points of view by J. Watson [3], A. Sayre [4], B. Maddox [5] and M. Wilkins [6] in fascinating books.

The study of globular proteins only took off later when, in 1934, J. D. Bernal and D. Crowfoot Hodgkin in 1935 (fig. 13) obtained the first X-ray single-crystal photographs of pepsin and insulin. The patterns contained thousands of reflections, as expected for crystals of large molecules. Dorothy Hodgkin then solved the structure of vitamin B12 and was awarded the 1964 Nobel Prize in Chemistry "for her determinations by X-ray techniques of the structures of important biochemical substances". The route was opened, but these studies also emphasized the difficulty of the task. In 1936 M. Perutz joined Bernal's lab and was soon inspired by his "visionary faith in the power of X-ray diffraction to solve the structures of molecules as large and complex as enzymes or viruses at a time when the structure of ordinary sugar was still unsolved". This was the beginning of his lifelong dedication to the study of crystalline haemoglobin. After a long battle in trying some very ingenious but unsuccessful methods to derive phase information, in 1953, triggered by the recent success in binding mercury to haemoglobin, he was led to propose the use of the *isomorphous replacement* method for the solution of protein structures. The full success of this idea was only achieved six years later, in 1960, when it led to the determination of the haemoglobin structure at 5.5 Å resolution. Meanwhile J. Kendrew had also applied isomorphous replacement to the smaller myoglobin molecule and succeeded in building an atomic model of the structure at 2 Å resolution. In 1962 M. Perutz and J. Kendrew were awarded the Nobel Prize in Chemistry (fig. 11). The following years were rich with theoretical, computational and instrumental developments, which allowed the solution of more protein structures. In 1972 the Protein Data Bank was established and

Fig. 12 Rosalind Franklin.

Fig. 13 Dorothy Hodgkin and J. D. Bernal (centre) with I. Fankuchen and D. Fankuchen.

Fig. 14 G.R. Levi.

Fig. 15 G. Natta.

the number of deposited coordinates of macromolecular structures has increased almost exponentially since then. The improvement of the isomorphous replacement technique was paralleled by new phasing methods, such as anomalous dispersion and molecular replacement, new refinement algorithms, their automation and the use of computer graphic tools for the interpretation of the electron density maps. There were progresses in instrumentation for data collection and synchrotron radiation was born. Increasingly larger structures of viruses and other biological assemblies could be solved: in 1982 A. Klug was awarded the Nobel Prize in Chemistry for "his structural elucidation of biologically important nucleic acid-protein complexes", in 1988 J. Deisenhofer, R. Huber and H. Michel were awarded the same Prize "for the determination of the three-dimensional structure of a photosynthetic reaction centre" and in 2003 R. MacKinnonn was awarded the Prize "for structural and mechanistic studies of ion channels" together with P. Agre. In more recent years the prize was awarded in 2006 to R. D. Kornberg "for his studies of the molecular basis of eukaryotic transcription", in 2009 to V. Ramakrishnan, T.A. Steitz and A. E. Yonath "for studies of the structure and function of the ribosome" and in 2012 to R. J. Lefkowitz and B. K. Kobilka "for studies of G-protein-coupled receptors".

The need for an international coordination of the crystallographic research activities was soon recognized in the early 1930's by Ewald and Bernal [7, 8] and formally realized by the establishment of the International Union of Crystallography (IUCr) (`http://www.iucr.org/`) in 1947 and its acceptance into the International Council for Science (ICSU). In 1948 the First General Assembly of IUCr was held at Harvard University and the journal "Acta Crystallographica" was launched. Today more than 40 countries are represented in the Union and "its objectives are to promote international cooperation in crystallography and to contribute to all aspects of crystallography, to promote international publication of crystallographic research, to facilitate standardization of methods, units, nomenclatures and symbols, and to form a focus for the relations of crystallography to other sciences". The 23rd Congress and General Assembly (`http://www.iucr2014.org/`) will be held in August this year in Montreal and will be the central event to celebrate the International Year of Crystallography (`http://iycr2014.org/`).

3 X-ray crystallography in Italy

In Italy [9] the first crystallographic studies using X-ray diffraction were carried out in Milan in 1923, when Giuseppe Bruni director of the General and Analytical Chemistry Laboratory in the Polytechnic Institute of Milan, aware of the importance of the new methodology, acquired, as war reparation, some X-ray diffraction equipments. He then charged Giorgio Renato Levi (fig. 14) with the setting up of the equipments and of the first structural investigations. Levi was soon joined by excellent co-workers: Giulio Natta, Adolfo Quilico and Adolfo Ferrari and the first papers on diffraction studies of $Ca(OH)_2$, $Mg(OH)_2$, $MgCO_3$, HgO and $LiF+MgF_2$ solid solutions, using powder diffraction (a technique learned by Levi from Debye and Scherrer in Zürich) appeared in 1924. The intense scientific activity produced several publications and the researches carried out in Milan were defined by Ewald (1962) as "of high quality and chemical importance". In 1938, Levi was forced to emigrate to Brazil by the fascist racial laws.

As is well known, Giulio Natta (fig. 15) received, together with Karl Ziegler, the Nobel Prize for Chemistry in 1963 "for their discoveries in the field of the chemistry and technology

of high polymers", but in his Nobel Lecture he reminded how he started in 1924 to use X-ray diffraction to study heterogeneous catalysts and only in 1932, after his meeting with Hermann Staudinger, he was attracted by polymers. To study them he also used diffraction, with the precious help of his co-workers Paolo Corradini and Giuseppe Allegra. Very important was the close collaboration with the leading chemical industry Montecatini, where Walter Ivano Bassi and Giuliano Fagherazzi contributed in a relevant way to the structural study of polymers.

A. Ferrari was the founder of the important school of chemical crystallography in Parma. His co-worker Mario Nardelli wrote in a colourful way: "From Ferrari's womb derived Luigi Cavalca, Mario Nardelli, Antonio Braibanti,…", and referring to his master he wrote: "In 1926 Ferrari was the first to point out his findings that "the diameter of an atom depends on its charge". Not a minor discovery in those days! L. Cavalca and M. Nardelli developed the Parma crystallography school and in 1942 the first X-ray generator was acquired and after the war Weissenberg cameras allowed single crystal work. The CNR Center for Structural Chemistry was founded in 1968 with a fairly large staff, and the group not only carried out a very relevant structural work, but also became leader in the continuous innovation of the instrumental and computational tools for crystal structure analysis.

In the mid 1930s Silvio Bezzi in Padova and Giordano Giacomello in Roma were the first to apply X-ray diffraction to the study of organic compounds and in 1954 they founded the first CNR Centers for Structural Chemistry, which soon initiated important research activities at an international level. S. Bezzi in 1937 moved his interest to structural chemistry and, helped by his co-workers Ugo Croatto and Vladimiro Scatturin, and later Edoardo Frasson, Carlo Panattoni and Mario Mammi, he devoted many of his papers to methodological and instrumental aspects of crystallography. Since 1947–1948 he promoted the creation of a computing centre and addressed his interest to crystallographic computing, the key that opened the new era of X-ray crystallography. His first structural study on p-dibromobenzene appeared in 1942 [10].

G. Giacomello in 1933 went to Vienna to learn from O. Kratky the diffraction techniques and published his first crystallographic papers on cholanic acids [11] with him. He then moved to Zürich to work with L. Ruzicka (Nobel Prize in Chemistry 1939) on steroids and terpenes. Finally, he went to Cambridge where he initiated the lasting collaboration with J. D. Bernal, D. Hodgkin and M. Perutz. He published some methodological papers on Fourier and Patterson methods, but most of his activity was on the structural analysis of several organic drugs in order to study the structure-activity relations. His first co-workers were Paolo Corradini and Alfonso Maria Liquori, who strengthened the relations with Bernal, Hodgkin and Perutz and opened the way to the birth of protein crystallography in Italy. In 1948, he became full professor in Rome, where the CNR Center for Structural Chemistry was created in 1954. Alberto Ripamonti and Alessandro Vaciago also contributed to its relevant activity.

At the Chemistry Institute in Turin, in the same years, Mario Milone after spending six months in 1934–1935 in Bragg's laboratory, in 1938 built an original "roentgen-photogonimeter" and with it he measured single-crystal data to solve the structure of Ni-dimethyl-glyoxime by Patterson analysis [12].

In these initial years, the analysis of diffraction data was still a very difficult art and all calculations were carried out by hand with the help of mechanical calculators and aids such as Beevers and Lipson strips. Only 2D data could be used and the solution was achieved from projections with rather limited accuracy: errors were always round the corner!

In Italy, morphological crystallography was traditionally studied in mineralogy institutes. The pioneer in the use of X-ray techniques was Ettore Onorato in Rome. His first papers appeared in the early 1930s. In 1926–1927, he was in Leipzig with E. Schiebold and acquired knowledge on the use of X-ray diffraction for the study of minerals. He then completed his preparation in Manchester working with W. L. Bragg. His initial works were on the characterization of minerals, such as gypsum and hydromagnesite and after the war he undertook the structural analysis of sanidine [13]. He was one of the founders of "Periodico di Mineralogia". Onorato was the first Italian to be elected in the IUCr Executive Committee in 1951 and he was entrusted the organization of the VI Congress and General Assembly in 1963 in Rome, a very important and successful event that promoted Italian crystallography in the world.

Also in Turin in the 1930s up to the early 1940s, some structural characterizations of minerals were carried out. Massimo Fenoglio initially used the X-ray generator with some cameras acquired by Clemente Montemartini at the Polytechnic Institute and from 1932 he employed X-ray diffraction to characterize several carbonate minerals. In 1938 a generator was acquired by the University, where Fenoglio was working with Edoardo Sanero and Mario Fornaseri. Only after the war did the institute acquire new instruments and the work was continued by Germano Rigault, Mariano Calleri and Giovanni Ferraris.

After the war Fiorenzo Mazzi, Giovanni Cocco and Lorenzo Garavelli graduated in Firenze with Guido Carobbi. Mazzi, after a short period in the USA, returned in 1956 to Florence and in 1960

Fig. 16 AIC (http://www.cristallografia.org/) logo and foundation assembly.

created in Pavia a strong X-ray crystallography group with international collaborations. CNR opened and equipped the Centre for Structural Crystallography, later Centre for Crystal-Chemistry and Crystallography, which promoted integration between crystallographic and petrological and geochemical researches. Mazzi has been and still is a reference person for his deep knowledge of crystallography. In the Pavia group initiated their career Sandro Coda, Giuseppe Rossi, Luciano Ungaretti and Elio Cannillo.

G. Cocco was the founder of the group in Perugia and had Pierfrancesco Zanazzi and later Romano Rinaldi as co-workers, while L. Garavelli went to Bari where he created a productive group with Carmelo Giacovazzo and Fernando Scordari.

The initial steps show how crystallography could develop in a climate of great interest and attention for scientific innovation that characterized the period bridging World War II, when CNR strongly supported Italian research. From this basis in the 1950s a solid network of laboratories could be set up, where diffraction techniques were developed and used to understand the structural properties of matter at an atomic and molecular level or, as it is now fashionable to say, at a nanometric level. The availability of modern crystallographic equipments and know-how and the advent of the first computers were the catalysts of an expansion of structural researches.

This expansion generated the need for a scientific coordination of the crystallographic activity in Italy. To create international collaborations in 1951 Italy, through the CNR, joined the IUCr. In 1966, the idea of creating a specific association was proposed by V. Scatturin at a CNR meeting in Rome and a committee for the statute was formed. In 1967, 108 crystallographers attended the foundation assembly of the Italian Crystallographic Association (Associazione Italiana di Cristallografia - AIC) (fig. 16), held in Rome, and approved the statute and opened the voting procedure to elect the Executive Council. The first AIC congress was held in Perugia in January 1968. Today AIC has around 300 members and in September the 43rd Congress will be held in Florence. In order to favor the diffusion of a crystallographic culture in Italy AIC organized a series of Schools, formerly located at villa "La Colombella" in Perugia, and more recently in various venues (http://www.aicschool.org). X-ray diffraction had, and still has, an important part in the Syncrotron Radiation Schools organized by SILS (http://www.synchrotron-radiation.it).

The main fields of structural investigations were:

- Chemical crystallography: Inorganic and metallorganic compounds, Organic compounds and drugs, Structure and conformation of polymers.
- Mineralogical crystallography: Characterization of new and rare mineral species, Modular crystallography, Crystal-chemical investigation of rock-forming minerals, Minerals and materials science.
- Biocrystallography: Protein crystallography,

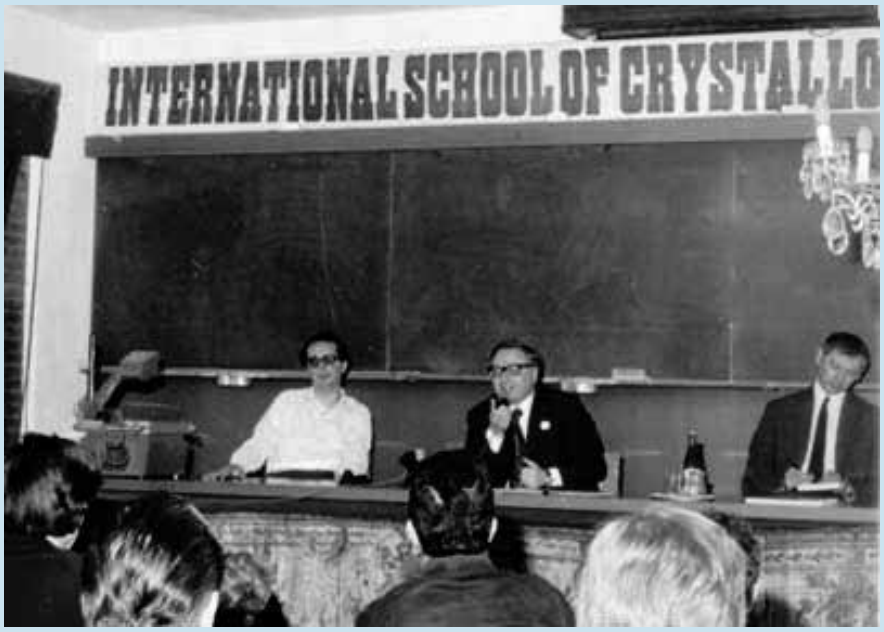

Fig. 17 Erice 1974: opening ceremony with L. Riva, S. Vaciago and M. M. Woolfson.

Conformational analysis of biological and synthetic macromolecules, Crystallographic study of biomaterials.
- Crystallography in materials science and crystal growth.
- Crystallographic methods: theoretical and experimental methodological aspects.

From 1970 expansion initiated: having acquired solid roots, Italian crystallographers could profit from the rapid improvements in computational hardware and software and in instrumentation: powerful mainframes and, more recently, almost as powerful personal computers, together with fully automated diffractometers.

In the late 1980s and early 1990s large synchrotron facilities to produce high intensity and collimated X-rays became available. ELETTRA in Trieste was inaugurated in 1994 and in the same year the Gilda Italian beamline at ESRF (Grenoble, France) became available.

The door was open for tackling increasingly complex problems in all the previously mentioned fields and crystallographic researches in Italy have gained international recognition. This is proved by the election of four Italian researchers into the IUCr Executive Committee (EC), and the nomination of M. Nardelli as president in 1987; C. Giacovazzo was the first president of the European Crystallographic Association (ECA) in 1997 and two other Italians have been in the EC; nine had important positions in the ECs of the International Mineralogical Association and of the European Mineralogical Union. Several Italian crystallographers were invited to give plenary lectures at international congresses or were chairpersons or members of IUCr and ECA Scientific Commissions. Other important recognitions are: IX European Crystallographic Meeting ECM-9 in Turin in 1985, XX IUCr Congress and Assembly in Florence in 2005, Trueblood award of the American Crystallographic Association to Angelo Gavezzotti in Salt Lake City in 2007, IUCr Ewald Prize to C. Giacovazzo in Madrid in 2011.

3.1 Important events

The first protein structures were solved in the years 1976-78 by the three groups in Naples (bovine seminal ribonuclease, Padua (ribonuclease S') and Pavia (Met-myoglobin from Aplysia limacina). Today in Italy there are more than 20 groups active in protein crystallography and their important researches acquired great international recognition.

In 1974 the first International School of Crystallography took place by the E. Majorana Center in Erice (fig. 17). Lodovico Riva di Sanseverino was the key person in developing the school to one of the most prestigious events in the crystallographic world, as recognized by the prize given to Lodovico (as he is known and remembered by all crystallographers) by the IUCr in 2005 in Florence. Paola Spadon greatly contributed to the success of the school and after the sudden death of Lodovico in 2010, she assured its continuation together with Annalisa Guerri.

In 1994 the Italian Synchrotron ELETTRA was inaugurated in Trieste and the first president was Carlo Rubbia, Nobel Prize

Fig. 18 X-ray diffraction beamline at ELETTRA.

Fig. 19 A logo of IUCr2005 in Florence and local organizers: (from left) A. Ienco, P. Rossi, P. Paoli (co-chair), A. Guerri, C. Mealli (chair).

for Physics in 1984. The crystallography beamline (fig. 18) was one of the first to be operational. Currently, 26 beamlines, including a storage-ring free-electron laser, utilize the radiation generated by the Elettra source.

In 1977, C. Giacovazzo published his paper on the Representation Theory and the SIR project, to develop an innovative direct method software for the solution of crystal structures [14, 15], was initiated as a collaboration between groups in Bari, Perugia, Rome and Turin. Today, the SIR program [16] is capable of solving large and complex crystal structures, including proteins diffracting to less than 2 Å resolution, and has been distributed to more than 6700 users all over the world. A parallel development has been the EXPO program [17] for the solution of structures from powder diffraction data, distributed to about 4200 users.

In August 2005, the World Congress of Crystallography was held in Florence (fig. 19). The Italian crystallographic community worked hard for a long time, initially by participating in the 1999 bid in Glasgow (where Italy was preferred to Japan) and then to organize the event. The XX IUCr Congress, thanks to the impressive work of the local organizers, is still remembered by world crystallographers as the most successful one for the number of participants (about 3000) and scientific quality (about 600 top level speakers). Funds were obtained from the European Union to support with scholarships about 450 participants. The quality of the services was high and the event is still considered memorable.

Recently Luca Bindi played an essential role in the recent adventurous discovery of the first natural quasicrystal [18].

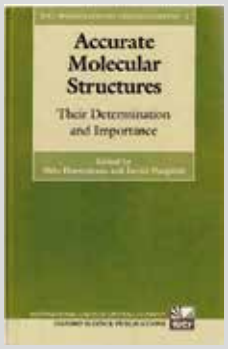

Fig. 20 Proceedings of the 1985 Erice Course on "Static and dynamic implications of precise structural information", edited by A. Domenicano and I. Hargittai.

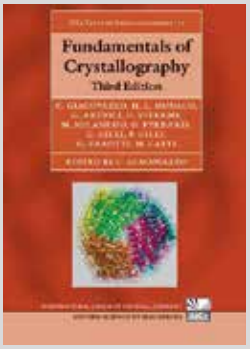

Fig. 21 Third edition (2011) of a comprehensive crystallography textbook edited by C. Giacovazzo.

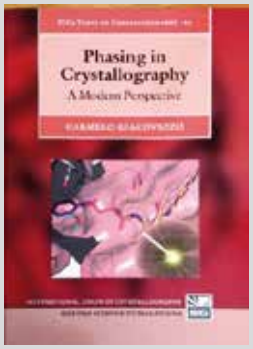

Fig. 22 A comprehensive monograph written by C. Giacovazzo illustrating the fundamental aspects and applications of Direct Methods (2nd edition 2013).

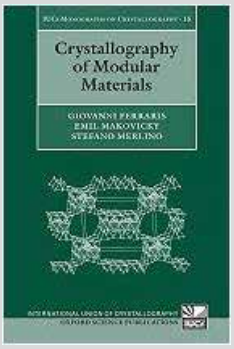

Fig. 23 A monograph written by G. Ferraris, E. Makovicky and S. Merlino on a topic of great relevance in materials science (published in 2004).

Fig. 24 A seminal monograph by A. Gavezzotti on intermolecular forces in condensed matter (published in 2006).

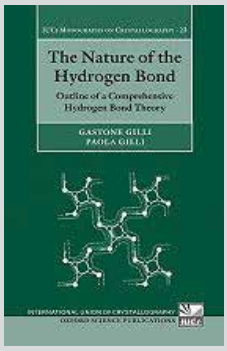

Fig. 25 A monograph written by G. and P. Gilli presenting the most comprehensive H-bond interpretation in terms of classical chemical bonding theories (published in 2009).

Fig. 26 Book on Cultural Heritage by G. Artioli.

3.2 Editorial activity

Italian crystallographers have contributed to a number of successful books published in the IUCr-OUP Texts and Monographs on Crystallography series (figs. 20, 21, 22, 23, 24, 25).

Finally, a very important recent text has been published by Gilberto Artioli (fig. 26), in which the essential role of diffraction techniques in answering many questions posed by the characterization and preservation of cultural heritage is clearly described. The pioneer on this topic in Italy has been Giacomo Chiari, who started his career in Turin and then was appointed Chief Scientist at the Getty Conservation Institute in Los Angeles.

4 Concluding remarks

X-ray diffraction provides an accurate picture of the three-dimensional structure of atomic and molecular systems: a picture is better than 1000 words!

Crystallography is a continuously developing science and Italian crystallographers are contributing in a relevant way to its development. Solving complex crystal structures is now often a routine job, but now more fundamental and difficult problems in chemistry, biology, earth sciences, physics and materials sciences can be tackled, often combining X-ray diffraction with other techniques: theoretical calculations, different spectroscopic methods, electron microscopy, kinetic studies, thermodynamic, etc. Therefore: Love diffraction, but do not leave It alone!

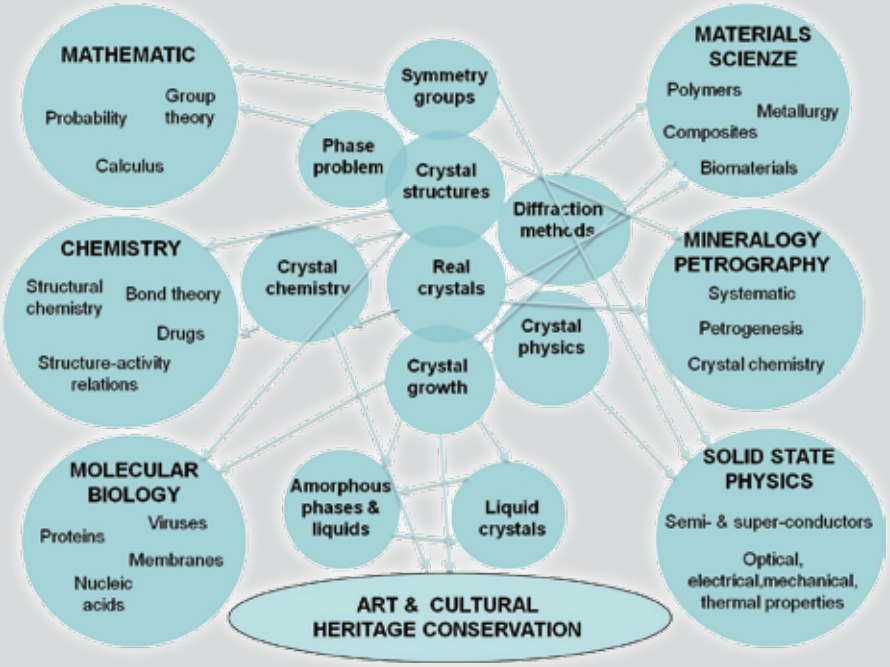

Fig. 27 Bubble diagram showing some of the links between the crystallographic techniques (smaller bubbles in the center) and other disciplines.

The fascinating interdisciplinary nature of crystallography is illustrated in the diagram of fig. 27.

Acknowledgments

This work would have been impossible without the constant involvement and help of the many Italian crystallographers who have provided precious documents and photographs, together with suggestions and criticisms. I am very grateful to Professor Authier and to Oxford University Press for allowing the reproduction of some of the figures of the book [1]. The photograph in fig. 18 is property of Elettra-Sincrotrone Trieste.

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