

# BIOGRAPHICAL MEMOIRS

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*S Chandrasekhar*

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Elected FRS 1983

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### INTRODUCTION

Sivaramakrishna Chandrasekhar died at the age of 73 years at his home in Bangalore. This sad news came from Chandrasekhar's daughter, Indira. She wrote:

My father had a mild heart attack followed by a stroke at the end of January, but he was recovering very positively. James, the children and I had been to see him only a few weeks ago. He was full of his usual enthusiasm and was planning various trips to conferences and meetings, and a paper on biaxial nematics, an idea that he had pursued for a long time, had just been accepted. It was a very happy visit. Since he was forced to slow down a little, he was able to relax and enjoy all the visitors who called on him. We were all shocked when he was struck down by a massive cerebral haemorrhage on the night of 7 March and are trying to face the grief and emptiness.

As this sad news spread, the sorrow of Indira and of her brother Ajit, and that of Chandrasekhar's wife Ila, was shared by all working in the field of liquid crystals, to which Chandrasekhar had devoted his scientific talents and efforts since the 1960s.

A very distinguished scientist, yet known affectionately simply as Chandra, he made many notable contributions to knowledge in the field of liquid crystals, a fact recognized by the many awards bestowed upon him, including Fellowship of the Royal Society in 1983. Despite his scientific stature, Chandra was a rather humble person, a truly gentle man, and these characteristics were occasionally found surprising by some who then experienced the rigour of mind that he applied to evidence and matters scientific.

Chandra was born in Calcutta, the fourth of five sons, three of whom became scientists. Dr S. Ramaseshan, seven years older, and Dr S. Pancharatnam (the youngest) were both well known in their fields. The leaning in the family to science was very strong, as several uncles

and cousins were well-known scientists, and his mother, Sitalakshmi, was the younger sister of Sir Chandrasekhar Venkata Raman, winner of the 1930 Nobel Prize for Physics. Chandra's father was Rao Bahadur S. Sivaramakrishnan, who started in civil service work for the Colonial British Government and rose to be Accountant General in independent India, before retiring to become adviser to the Government of Punjab. As a result of his father's government service, the family often moved to different cities and Chandra's schooling was much interrupted. Chandra did not enjoy these changes, but despite this he did very well and left with distinction aged 13 years to join the highly reputed, Jesuit-run Loyola College in Madras, where he stayed for two years. He then went to Nagpur University, where he obtained his MSc honours degree coupled with two gold medals, and later the degree of PhD. He then moved to Bangalore to join the newly opened Raman Research Institute; he was the first research scholar there, under the direction of his uncle Sir C. V. Raman, but their relationship was always that of professor and student, never uncle and nephew. He was soon joined at the Institute by other scholars such as Professor Ramdas and Professor Krishnamurty, and Dr Bhatt, Dr Jayaraman and Dr Viswanathan. At this time he met his future wife, Ila, at his elder brother's house. Dr Ramaseshan was then at the Indian Institute of Science, and he and his wife kept open house, allowing the Tuesday Science Club, involving the Raman Institute scientists, to hold discussions there. Chandra and his fellow scholars had a monthly stipend of only 250 rupees, hardly enough to buy a good meal today. Despite this Chandra managed to buy a motorcycle, a Matchless, and together with Ila as pillion passenger, they probably scandalized the conservative Bangalore residents by riding around the suburbs. Later, unfortunately, a pedestrian caused him to fall from his motorcycle; Chandra suffered a head injury, which, following a childhood head injury sustained when horse riding, resulted in his being often plagued by headaches.

Chandra and Ila did have some problems over marrying. Belonging to two different language groups from widely different areas of their vast country, family objections were raised. However, Chandra's parents and Ila's father gave them support and they were married in 1954. That year, Chandra won an 1851 Exhibition Scholarship and they left India for England and Pembroke College, Cambridge. They were happy there from 1954 to 1957, living in Kettle's Yard in a flat of the Garden House Hotel; Chandra worked as a research student at the Cavendish, which was then in Free School Lane. After this, Chandra was a Department of Scientific and Industrial Research Fellow and member of staff in the Department of Crystallography of University College London, and then, from 1959 to 1961, he was a Research Fellow at the Davy Faraday Laboratory of the Royal Institution in London. Many years later, Chandra returned to Cambridge as Nehru Visiting Professor and Fellow of Pembroke College. In his letter of condolence, the Master of Pembroke, Sir Roger Tomkys KCMG DL mentioned that Chandra was going to be offered an Honorary Fellowship at Pembroke, but unfortunately it was too late. Chandra held the degree of ScD (1987) from the University of Cambridge and was a Fellow of the Institute of Physics in London.

Return to India in 1961 saw Chandra setting up the new Department of Physics at the University of Mysore, where the campus was wild land attached to the estates belonging to Princess Leelavathi of the Mysore royal family. Even after clearance, the land was still frequented by jackals, huge owls and even leopards. The Physics Department was started in unoccupied parts of the palace, which were taken over at night by myriads of bats. Chandra's brother Dr Pancharatnam was with him at that time, and scientific discussions were often held by candlelight when the electric power failed. Chandra remained at Mysore University as head of the Department of Physics until 1971, gathering round him a group of young researchers. It

was there that Chandra began to think seriously about moving out of the solid crystal field and into that of liquid crystals. One important factor was the increasing sophistication and cost of X-ray equipment needed to be competitive in solid crystal work, and Chandra knew that in India he could not afford this. He was also influenced by a conversation with Sir Lawrence Bragg FRS, from whom he received strong support for the change and later by an invitation from Professor Glenn Brown to attend a Liquid Crystal Conference planned for 1965 at Kent State University. This invitation arose from advice from Nobel Laureate Professor Dorothy Hodgkin FRS, who agreed that liquid crystals needed more attention, especially from physicists, but that rather than she herself a young Indian physicist, namely Chandra, should be invited to talk, prophesying that he would soon make major contributions. How right she was! He and his group at Mysore therefore began work probing the physics and physical properties (electrical, magnetic, optical and thermodynamic) of this fascinating condensed state of matter.

In 1971 Chandra was invited back to the Raman Research Institute in Bangalore to set up the famous Liquid Crystal Research Laboratory, where he and his group were so productive and became world-renowned for their practical and theoretical work in liquid crystals. His research earned Chandrasekhar great respect and admiration, and it was very appropriate that after his 60th birthday in 1990 a two-day symposium was held in 1991 at the Massachusetts Institute of Technology to mark the occasion. During this period at the Raman Institute, Bharat Electronics of Bangalore collaborated closely with his group, and later the company made available a building in which a new Centre for Liquid Crystal Research was set up by Chandra when, in 1991, he retired from the Raman Institute after 20 years. The Centre was formally inaugurated by Mr K. R. Narayanan, Vice-President and later President of India, and with Chandra as Director it rapidly gained a worldwide reputation. It was from here, in 1992, that the second edition of Chandrasekhar's monograph entitled simply *Liquid crystals* was published by Cambridge University Press. First published in 1977, the book is hailed internationally as a classic. It was here in the Centre for Liquid Crystal Research that Chandra carried on his fine work until his death in 2004.

## SCIENTIFIC RESEARCH

### *Solid crystals*

In 1951, at the Raman Research Institute, Chandrasekhar investigated the optical rotatory dispersion of crystals. He set up an experiment to measure the temperature dependence of the optical rotatory dispersion and used it to study a number of crystals, including quartz (1)\*, sodium chlorate and cinnabar (2). Later, he spent some of his time in the UK thinking about his optical rotatory dispersion results and succeeded in showing that the entire range of data, from the visible up to the far ultraviolet, can be accurately represented by the simple formula

$$\rho = k\lambda^2/(\lambda^2 - \lambda_0^2)^2,$$

where  $\rho$  is the optical rotation,  $\lambda$  is the wavelength,  $\lambda_0$  is the characteristic wavelength and  $k$  is a proportionality constant related to the crystal structure, rather than by the Drude-type formula previously used. On his return to India in 1961, he resumed his experimental studies and went on to publish two further papers on mixed crystals of sodium chlorate and sodium bromate.

\* Numbers in this form refer to the bibliography at the end of the text.

In 1954 Chandrasekhar moved to Pembroke College, Cambridge, to work in the Cavendish Laboratories on X-ray scattering from solid crystals. The research was supervised by Dr H. D. Megaw and Dr W. H. Taylor, and the PhD thesis title was ‘The structure of body-centred anorthite and some observations on extinction in crystals’. The particular problem he investigated was a long-standing difficulty related to extinction errors in the X-ray analysis of crystals caused by the existence of imperfections or the ‘mosaic’ nature of the crystal. Chandrasekhar suggested a method for correcting for this error by using polarized X-rays (3) and in two later appointments in the UK he followed up his suggestion by developing a simple experimental method (4) based on his ideas. The first of these appointments was at University College London from 1957 to 1959, working with Dame Kathleen Lonsdale FRS, followed by two years at the Royal Institution with Sir Lawrence Bragg and David (later Lord) Phillips (FRS 1967). Some further work in this field followed on his return to India in 1961, but his enthusiasm for this area soon became overtaken by his new interest in liquid crystals.

#### *Liquid crystals*

Chandrasekhar initiated his studies on liquid crystal (LC) systems when he returned to the University of Mysore in 1961 as Professor of Physics. At that time, few people were aware of the existence of these materials. To quote his own words:

When I was setting up the new department at Mysore, I made up my mind to change my field from solid crystals to liquid crystals. My knowledge of these intermediate phases was, at that time, limited to brief accounts I had come across as a student more than 10 years earlier in books published in the 1930s, but I was determined to make the change. With some trepidation, I mentioned this to Bragg, hoping that he would not be too disappointed that I was wandering off into an unfashionable and long-forgotten field. His response was, in fact, just the opposite, for which I was truly grateful. He started a serious discussion on the subject and I felt jubilant.

As the department at Mysore was new, experimental facilities took time to establish, and Chandrasekhar’s initial studies were mainly theoretical. He was attracted towards extending his work on the optical rotatory dispersion and X-ray scattering of solid crystals to understand the large rotatory power and rotatory dispersion found in cholesteric (chiral nematic) LCs. In these, chiral molecules impart a helical ordering on the normal LC order. When the pitch of this helix is similar to the wavelength of visible light, selective reflection of one sense of circular polarization takes place and the wavelengths of the reflected maxima vary with the angle of incidence in accordance with Bragg’s law. Although earlier models of the optical properties of chiral nematic LCs had been proposed, Chandrasekhar derived a simpler model that gave accurate results and was useful in elucidating the optical properties and suggesting new analogies with X-ray scattering. He achieved this by applying Darwin’s dynamical theory of X-ray diffraction to the optical properties of chiral nematics (8) and realized that there must be an optical analogue in chiral nematic LCs to the Borrmann effect in solid crystals. He subsequently confirmed experimentally the analogous optical effect in absorbing cholesteric media in the vicinity of the selective reflection band. Chandrasekhar remained fascinated by the optical properties of LCs, and of chiral nematics in particular, and it was a topic to which he kept returning with enthusiasm. Chandrasekhar’s main interest was always in pure, rather than applied, research, so it is interesting to note that he has left an important legacy that has been of great use to the LC display industry. Modelling of the optical properties of LC displays and their accompanying optical films is of importance in the optimization and design of displays. The modelling depends on the application of

Jones calculus, and Chandrasekhar was one of the first to apply this to helical LCs (5); he was quite probably the first to derive the Jones matrix of the ubiquitous twisted nematic LC device.

Chandrasekhar also became interested in the orientational order present in LCs, which is fundamental to their unique properties. This was initially a theoretical study applying the Pople–Karasz theory of melting and orientational transitions in molecular crystals consisting of anisotropic molecules to calculate a general phase diagram including both melting and LC phase transitions. This theoretical interest grew into later experimental studies that he made on the influence of high pressures on LC order and phase transitions; by applying suitably high pressures, Chandrasekhar was able to induce LC phases in compounds that otherwise did not show them (9). A rather subtle anomaly in LC order that had been known for some time began to attract Chandrasekhar's attention. The molecular field theories being used to describe LC order tended to overestimate the strength or enthalpy of the first-order phase transition from LC to isotropic. Chandrasekhar recognized the relevance of near-neighbour correlations and developed a theory (6), based on a method originated by Bethe for treating order–disorder effects in binary alloys, which improved the theoretical predictions. There was, however, a more graphic illustration of the general concept of near-neighbour correlations. Many LCs have a large dipole moment along the molecular long axis, and he realized that the energy of interaction between neighbouring molecules was significant and should induce a local antiparallel ordering of molecules that needed to be included in the theory. Within a short time there was direct evidence of this local antiparallel ordering from X-ray studies of these polar LC molecules. Another consequence was also predicted, and subsequently confirmed experimentally by Chandra, on a change in the mean dielectric constant either side of the transition from LC to isotropic caused by the interaction between the LC order and the local antiparallel order. It is noted that there is an important practical consequence of this antiparallel order in the everyday LC calculator. The presence of the local antiparallel order was inhibiting the use of the twisted nematic LC display in calculators, and as a result all the displays used employ polar LC materials in which the local antiparallel order has been deliberately removed by the addition of a small amount of non-polar LC materials.

Chandrasekhar had a great interest in, and depth of understanding of, the various anisotropic properties of LC materials, but it was not an area to which he devoted much research time. The most notable exception was his publication of a simple and direct method to measure the notoriously difficult twist elastic constant (7). In contrast, the chapter in Chandrasekhar's book *Liquid crystals* (18) on the anisotropic physical properties and continuum theory of the nematic phase is not only the longest, but it also remains one of the most complete pieces of writing on the subject. It combines a wonderful depth of understanding of the physics involved with a precise mathematical rigour and is essential reading for new students in the field.

#### *Discotic liquid crystals*

Chandrasekhar (10) and his colleagues B. K. Sadashiva and K. A. Suresh must have experienced great satisfaction when they prepared and isolated the hexa-esters of 1,2,3,4,5,6-hexahydroxybenzene with simple open-chain alkanic acids and discovered that several of the esters did indeed form a new type of LC phase. When heated to a temperature above the melting point of the crystals, enantiotropic (occurring on both heating and cooling cycles) LC phases were formed and had reasonable thermal ranges before becoming isotropic at the upper



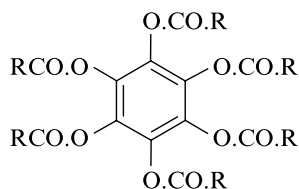


Figure 1. Hexa-ester of 1,2,3,4,5,6-hexahydroxybenzene and an acid  $\text{RCO}_2\text{H}$ .

transition temperature. This discovery provided verification that molecules of disc-like shape can form LC phases, and that a simple rod-like shape is not the sole prerequisite for mesomorphic behaviour. The possibility that disc-shaped or leaf-shaped molecules might form LC phases had earlier been mentioned briefly by D. Vorländer and suggested on theoretical grounds by P. G. de Gennes and by L. D. Landau. The actual discovery of such a phase by Chandrasekhar was therefore of enormous significance in the field of liquid crystals, and it led to many publications in a very short time describing the formation of discotic LC phases by a range of molecules of disc-like shape and exploring their properties.

Chandrasekhar's hexa-*n*-alkanoates of hexahydroxybenzene (BH) have the structure shown in figure 1, with the chain lengths of the alkyl groups (R) ranging from *n*-pentyl to *n*-nonyl, but before looking at transition temperatures for the esters BH6 to BH10 it is necessary to mention the nomenclature for the new discotic phase. After a number of proposals, that adopted by Chandrasekhar was K for crystal, D for the discotic phase and I for the isotropic liquid. However, this caused confusion with the earlier use of D to describe a cubic phase formed by certain nitrobiphenyl carboxylic acids.

Today, the accepted symbol for a phase consisting of a columnar arrangement of disc-shaped molecules is Col, with variants being indicated by subscript letters. The crystal phase is now represented by Cr rather than K. For Chandrasekhar's new compound BH7 with  $\text{R} = \text{C}_6\text{H}_{13}$  the transition temperatures were Cr 81.2 °C Col 87.0 °C I, and for BH8 with  $\text{R} = \text{C}_7\text{H}_{15}$  the transition temperatures were Cr 79.8 °C Col 83.4 °C I. The two discotic phases were therefore enantiotropic. With  $\text{R} = \text{C}_5\text{H}_{11}$  and  $\text{C}_9\text{H}_{19}$  the esters formed only the isotropic phase on heating, because the melting temperatures were higher, at 94.5 and 85.5 °C, respectively. The remaining ester with  $\text{R} = \text{C}_8\text{H}_{17}$  melted to the isotropic liquid at 80.4 °C, but on cooling the melt a monotropic Col phase was formed at 76.6 °C.

As early as 1965, LC behaviour had been observed by Brooks & Taylor (1965) at high temperatures during the carbonization of graphitizable organic materials involving large plate-like molecules. These phases are now accepted as discotic. In addition, Eaborn & Hartshorne (1955) had reported LC behaviour for the melt of diisobutylsilanediol, and later work (Bunning *et al.* 1980) showed that the basic unit is a dimer and the phase is discotic and miscible with Chandrasekhar's ester BH7. It is abundantly clear, however, that all credit must go to Chandrasekhar for discovering these new discotic hexa-esters and for launching a period of great activity in studying the structures and properties of these LC systems.

From Chandrasekhar's thermodynamic, optical and X-ray studies it was clear that the new mesophases were quite unlike the classical phases of calamitic LC materials, namely those consisting of rod-like molecules. The proposed model of disc-like molecules stacked aperiodically on top of one another to form liquid-like columns that are then packed hexagonally has stood the test of time. As noted by Chandrasekhar and his colleagues (11), the structure has

translational order in two dimensions but not in the third, and it was therefore the first example of a system ‘melted’ in one dimension. His new discotic phases were therefore columnar, each column having a rigid aromatic core and a soft outer envelope of hydrocarbon chains. Chandrasekhar went on to elucidate, in terms of the columnar model, the beautiful birefringent textures given by thin films of his hexa-esters when viewed by optical microscopy, and from pressure studies on his esters one result was that the monotropic discotic phase of the ester BH9 became enantiotropic at quite low pressures.

Stemming from Chandrasekhar’s studies (12) of the new phases, interest rapidly grew worldwide, the first developments in 1978–79 coming with reports by Billard *et al.* (1978), Dubois (1978) and others that hexa-substituted esters and ethers of triphenylene also form columnar LC phases. These studies led on to the X-ray studies of Ann-Marie Levelut (Levelut 1979), which confirmed conclusively the hexagonal columnar mesophase structure. The nomenclature system for the new LC phases could now be developed as more discotic systems were discovered and their phases were studied. For example, rectangular (r) as well as hexagonal (h) stackings of columns were found, and it became necessary to distinguish disordered (d) from ordered (o) stackings of the molecules within a given column. As a result, Col<sub>ho</sub>, Col<sub>hd</sub>, Col<sub>ro</sub> and Col<sub>rd</sub> phases were established. The symbol t was also necessitated to denote discotic phases (Col<sub>t</sub>) with tilted columnar stackings of the molecules formed by certain hexa-4-n-alkoxybenzoate esters of hexahydroxytriphenylene. These were first reported by Destrade *et al.* (1979), who also drew attention to the first discotic nematic phases (not columnar, and symbolized by N<sub>D</sub>). For example, the hexa-4-n-octyloxybenzoate ester of hexahydroxytriphenylene had the transitions Cr 152 °C Col<sub>t</sub> 168 °C N<sub>D</sub> 244 °C I. In the N<sub>D</sub> phase the molecules lie with their planes parallel but with their centres disordered, and capable of sliding about like pennies on a plate.

Today, hexa-esters of rufigallol and of truxene, and many other systems of disc-shaped molecules, are known to form discotic LC phases. Destrade *et al.* (1980) also went on to prepare disc-shaped triphenylene derivatives with six optically active alkanoyloxy groups. Although a twisted discotic nematic phase (N<sub>D</sub><sup>\*</sup>) was not formed by the pure compounds, which were in fact Col<sub>h</sub> or Col<sub>r</sub> in type, such a phase was formed by mixtures of the chiral materials with hexaheptanoyloxytriphenylene, which in the pure state gives the simple N<sub>D</sub> phase. In this new phase there are layers of molecules in which the discs are stacked on edge parallel to one another but in a random disposition. However, the planes of the molecules in each layer rotate progressively through some angle in passing up or down through a stack of layers. This is the discotic nematic analogue (N<sub>D</sub><sup>\*</sup>) of the calamitic chiral nematic phase.

After the first excitement arising from Chandrasekhar’s discovery in 1977, new molecular systems exhibiting discotic phases became molecularly more complex and difficult to prepare, and Chandrasekhar, as a physicist, concerned himself mainly with thoroughly establishing the physical behaviour and properties of available pure discotic systems. For example, we may quote his heat-capacity and high-pressure studies, his miscibility studies of discotic materials, his examination of very detailed aspects (such as dislocations and disclinations) of the beautiful optical microscopic textures of the discotic phases, and his studies of the spacings and mutual arrangements of the aromatic cores as well as of the entire disc-like molecules in the different discotic phases. All these studies have been of great importance. He also examined (18) in detail the extension of W. L. McMillan’s molecular field model (McMillan 1971) of the calamitic smectic A phase to hexagonal discotic systems so that the density wave was now periodic in two dimensions. This led to improvements in the theoretical plot of transition temperatures against alkyl chain length for homologous series in which, experimentally, N<sub>D</sub> phases

occurred at higher temperatures than  $\text{Col}_h$  phases. He also investigated theoretical aspects of the transition from  $\text{Col}_h$  to  $\text{Col}_r$  and the application of continuum theory to fluctuations in the columnar phase and their role in light scattering and other physical properties. The potential of discotic systems for practical applications was also of interest to Chandrasekhar and his colleagues, for example the one-dimensional conductivity of well-aligned samples of  $\text{Col}_h$  phases and their behaviour as ‘molecular wires’ (21). However, it is another property of discotic LCs that has achieved widespread use in LC displays. The optical anisotropy of the disc-like molecules is of opposite sign to that of conventional calamitic LCs, and discotic liquid crystals are now widely used in optical compensation films to improve the optical performance of twisted nematic LCDs in desktop and laptop computer monitors.

The worldwide outburst of research activity referred to earlier that soon followed Chandrasekhar’s discovery of discotic LC systems was testimony to the great importance of this event in 1977. Although the number of materials known today to exhibit discotic phases must be more than 2000, there is no doubt that, as their discoverer, Chandrasekhar’s name will always be the one most intimately associated with these fascinating systems.

#### *Biaxial nematic liquid crystals*

New states of matter are occasionally discovered by chance, whereas at times their discovery is driven by theory. The biaxial nematic state is an example of the latter mode of discovery, with Chandrasekhar having a major role in the hunt for what has proved to be an elusive LC state. The common nematic phase has uniaxial symmetry, but Freiser (1970) predicted, on the basis of a molecular field theory, that the biaxial symmetry of mesogenic molecules should lead to a biaxial nematic phase,  $\text{N}_B$ , in addition to the uniaxial nematic,  $\text{N}_U$ . These two phases differ in that properties such as the anisotropic dielectric tensor should have two independent components for the biaxial nematic, whereas there is just one for the uniaxial phase. It was only after 10 years that Yu & Saupe (1980) discovered the biaxial nematic phase, but for a lyotropic system and not for the thermotropic LCs for which it had been predicted. There the matter rested until 1984 when, in a Plenary Lecture to the 10th International Liquid Crystal Conference in York, Chandrasekhar reviewed the unusual properties that a biaxial nematic should possess (13). He then explained the importance of having examples of thermotropic  $\text{N}_B$  phases and proceeded to speculate on molecular features that compounds likely to form this phase should possess. Given his knowledge of discotic LCs it seemed natural to him that a perturbed elliptical disc might form a biaxial nematic.

Subsequently he thought that such a biaxial elliptical shape might be achieved by combining, in a single molecule, features of discs and rods. He proposed this idea to B. K. Sadashiva and suggested that he should attempt to prepare such compounds. However, none gave any indication of an  $\text{N}_B$  phase. Independently, Sadashiva, working on disc-like metallomesogens, had prepared two copper complexes that formed some of the first paramagnetic nematics (14). One of these, bis[1-(4-n-decylbiphenyl)-3-(4-ethoxyphenyl)propane-1,3-dionato]copper(II), has the structure in figure 2. When Chandra saw this he immediately realized that it combined the rod-like and disc-like features that he required and that the nematic phase might well be biaxial. The next challenge was to demonstrate, unambiguously, the biaxiality of the nematic phase, a problem that has bedevilled the discovery of this phase. He decided that conoscopy was the appropriate technique to determine the phase symmetry and set B. R. Ratna with V. N. Raja the challenging task of obtaining the conoscopic images. Their careful measurements, published in 1988 (16), showed that the sample exhibited a unique Landau point at which the

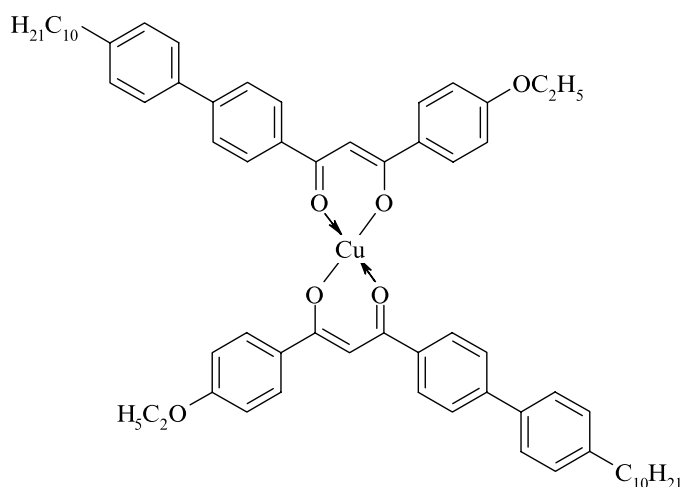


Figure 2. The molecular structure of a copper complex thought to exhibit a biaxial nematic phase.

isotropic phase underwent a transition directly to a biaxial nematic. It was also shown that the addition of a small amount of a calamitic nematogen induced a uniaxial nematic before the biaxial nematic, as expected. The way now seemed open for detailed physical measurements that Chandrasekhar had called for; indeed, he studied the optical textures (15) and the X-ray scattering patterns (17) of the nematic formed by the copper complex, which seemed to support its identification as biaxial. Another benefit of this discovery was the encouragement that it gave to others for the design of compounds likely to form biaxial nematic phases. Indeed, one such system had been reported by Malthête *et al.* (1986) in which the constituent molecules clearly combined the rod and disc features anticipated by Chandrasekhar. However, on detailed examination the identification of the nematic phase as biaxial proved to be false (Hughes *et al.* 1997).

In coming years other groups joined the search for compounds likely to form the thermotropic biaxial nematic phase; noteworthy was the work of K. Praefcke in Berlin on their molecular design (Praefcke *et al.* 1991). Given the complementary nature of their expertise it was inevitable that Chandrasekhar and Praefcke would collaborate, and the subject was the mesogen 4,4'-di-(2,3,4-tridodecyloxybenzylidenamino)-*p*-terphenyl, again combining rod-like and disc-like features. The characterization of the nematic phases of this material was especially thorough, based on optical microscopy, conoscopy and the optical anisotropy for a homeotropic sample (19). The results of these measurements show the clear but unexpectedly small biaxiality of the sample. In addition, there seemed to be a distinct difference in the Schlieren textures of the two nematic phases; for the  $N_U$  phase both two-brush ( $|s| = \frac{1}{2}$ ) and four-brush ( $|s| = 1$ ) disclinations are present, but in the  $N_B$  phase only two-brush disclinations appear. This behaviour has been investigated in detail to see whether sample surfaces influence the absence of four-brush disclinations, and it seems that they do not (20). On the basis of an argument concerning the inability to stabilize the  $|s| = 1$  defects by the minor directors of the  $N_B$  phase escaping into the third dimension, it was claimed that the absence of such defects could be the signature of the biaxial nematic phase. If true, this would be a

powerful method to determine, unambiguously, the symmetry of a nematic phase; however, simulations suggest that when the biaxial ordering is weak the  $|s|=1$  disclinations can be stabilized by an escape of the main director into the third dimension, as in the  $N_U$  phase (Chiccoli *et al.* 2002).

It is fitting that the last paper to be published by Chandrasekhar, and of which acceptance was recounted excitedly to his daughter, should be concerned not only with a biaxial nematic but in addition a biaxial smectic A phase (22). Now the molecular structure was not the familiar combination of rod-like and disc-like features but possessed rod-like and bent-core or banana-like features with the two mesogenic moieties linked by a flexible spacer; this is certainly a structure capable of existing in many biaxial conformations. The compound formed nematic and smectic A phases; investigation of these with the use of techniques developed for biaxial nematic phases suggests that both phases are biaxial. This non-symmetric LC dimer seems to provide the first example of a transition from biaxial smectic A to biaxial nematic; this represents an exciting observation demanding further investigation.

By design of compounds and exploration of physical techniques, Chandrasekhar certainly made very significant contributions to the hunt for the thermotropic biaxial nematic phase. However, above all he stimulated a wide interest in this elusive phase, with its considerable importance and potential.

#### NATIONAL AND INTERNATIONAL AWARDS AND HONOURS

In 1983, Chandrasekhar was elected a Fellow of the Royal Society and in 1994 Her Majesty The Queen, on the recommendation of the Council of the Royal Society, awarded him a Royal Medal of the Society. Only one other scientist of Indian origin, his cousin, the distinguished astrophysicist and Nobel laureate, Professor Subrahmanyan Chandrasekhar FRS, had received this honour—35 years earlier. Further honours followed: in 1998, in Paris, he received the Niels Bohr–UNESCO Gold Medal for outstanding contributions to the development of liquid crystals, the advancement of science in developing countries and the teaching of physics. In the same year he received Honoured Membership of the International Liquid Crystal Society, of which he became in 1990 the First (Founder) President. Then, in 1999, the Government of France bestowed upon him the title Chevalier dans l'Ordre des Palmes Académiques for his outstanding research, and in 2000 he was awarded the V. K. Freedericksz Medal of the Russian Liquid Crystal Society for his outstanding research in liquid crystals.

Chandrasekhar was a Fellow of the Indian National Science Academy and its Vice-President from 1989 to 1990, a Fellow of the Indian Academy of Sciences, and a Founding Member of the Indian Physics Association. He also worked tirelessly for the development of science in poorer countries and was a Founding Fellow of the Third World Academy of Sciences, Trieste. His scientific stature was also acknowledged in many ways nationally in India: honorary DSc from the University of Mysore in 1989, the Silver Jubilee Award and then the Shanti Swarup Bhatnagar Prize for Physical Sciences of the Council for Scientific and Industrial Research in 1972, the award in Physical and Mathematical Sciences of the Federation of the Indian Chambers of Commerce and Industry in 1979, the C. V. Raman Award of the University Grants Commission in 1981, the Mahendra Lal Sircar Award for Physics of the Indian Association for the Cultivation of Science in 1984, the Karnataka Rajyotsava Award of the Karnataka State Government in 1986, the Homi Bhabha Medal of

the Indian Association for the Cultivation of Science in 1987, the C. V. Raman Centenary Medal of the Indian Association for the Cultivation of Science in 1988, the Jawaharlal Nehru Award for Science of the M. P. Council of Science and Technology in 1991, the Meghnad Saha Medal of the Indian National Science Academy and the R. D. Birla Award of the Indian Physics Association in 1992, the C. V. Raman Birth Centenary Award of the Indian Science Congress in 1993, and decoration with the Padma Bhushan by the Government of India in 1998.

### SOME PERSONAL REMINISCENCES

Chandrasekhar did a great deal over a period of 30 years for the promotion of science teaching and its development, both in India itself and in developing nations. He was a member of the Executive Council of the Association of Asia Pacific Physics Societies, of the Physics Action Council of UNESCO and of the International Commissions on Physics Education and on 'Science for Peace.' He became Founder President of the Indian Liquid Crystal Society in 1992, and was an active President of the International Liquid Crystal Society. He was also the saviour of the Ninth International Liquid Crystal Conference, as the following statement explains:

The ninth conference was originally scheduled to take place in Krakow, August 30 – September 3, 1982, but unfortunately, Professor J. A. Janik and his colleagues faced many practical difficulties because of the situation that had developed in Poland. In spite of every effort on the part of Professor G. W. Gray, Chairman of the International Planning and Steering Committee, to avoid a cancellation of the Krakow meeting, it became clear by April of this year that alternative arrangements would have to be made. Accordingly, the Planning and Steering Committee decided to invite us to organize the ninth conference in Bangalore.

And so the conference was held there, to everyone's relief. For this, the international liquid crystal community owes a debt of gratitude to Chandra, his wife, Ila, and their daughter, Indira, and many of her friends who worked tirelessly to make the meeting happen in such a short time and be such a memorable success. To those who attended, the quality of the science was excellent, but their memory must surely be of a wonderful evening in the grounds of the Raman Institute on the occasion of the conference banquet, at which the quality of the food was superb (guaranteed by Ila herself), as was the following entertainment provided by Indian national dancers and singers. Throughout the meeting, too, proceedings were graced by Ila and by Indira and her friends, dressed in beautiful national dresses, as they dealt with the questions and slight concerns typical of conference delegates. The family Chandrasekhar certainly did a wonderful job.

Indeed, after that, Ila frequently accompanied Chandra to the biennial International Conferences, and she became a friend of many of us, the delegates. The sight of Chandra and Ila was a familiar one at meetings, lending a warmth and a happy familiarity to whatever the surroundings were. It is such a picture which many of us will carry from one of the last conferences attended by Chandra, together with Ila and Indira. This was an International Conference to celebrate the 25th anniversary of Chandra's seminal paper on discotic liquid crystals, which was held in the Abdus Salam International Centre for Theoretical Physics in Trieste in November 2002, and although Chandra was in somewhat failing health, he acted as Conference Chairman with his usual efficiency and took an active part in all the discussions.

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