Michael Faraday· Discovery of Electromagnetic Induction

S Chatterjee

Sabyasachi Chatterjee obtained his PhD in condensed matter physics from the Indian Institute of Science, Bangalore. He now works at the Indian Institute of Astrophysics. His current interests are in the areas of galactic physics and optics. He is also active in the teaching and popularising of science.

Michael Faraday began his studies on electricity in 1821, i.e. a year after Oersted's discovery of magnetic effects of electric currents. What prompted Faraday to make these studies was not any special interest he had in the field but that he was requested by his friend R Phillips to write a historical account of the work on electricity and magnetism for the journal *Annals of Philosophy*. In 1821, Faraday's career as a scientist stood at the crossroads. Son of a poor blacksmith, Faraday had been earning his living as a bookbinder, since his childhood. He not only bound books but also read them. Later he attended the lectures by Humphry Davy at the Royal Institution and surprised Davy by producing a summary of his lectures. Impressed by the young lad's ability to appreciate the core of scientific problems, Davy offered Faraday a job in 1813 at the Royal Institution.

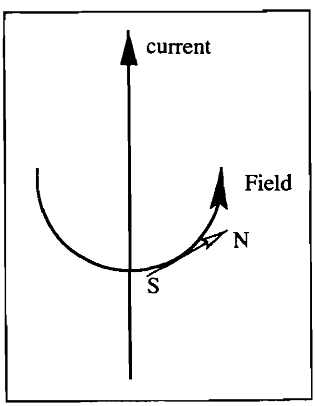
Faraday was Davy's assistant. He benefitted enormously from Humphry Davy's magnanimity. But later Faraday's rapid rise made Davy jealous and he became indifferent to him, treating him more as a challenger. In 1821, Faraday was known primarily as a chemist and metallurgist. So it is not known why he was asked to review the work on electricity. But what he did was to be of momentous consequence not only to the discipline that he undertook to study but also to the course of history.

Faraday began writing his review in the summer of 1821. He went through all the reports that had been published till then. He also repeated the experiments done by others. He had a good reputation as an experimenter, not merely because of his skill with his hands and his keen powers of observation but also because he possessed a critical mind which did not allow him to accept an explanation without judging its consistency and without exploring possibilities of further experimental proofs.

Keywords
Electromagnetism, lines of force, induction, field.

Magnetism was known to mankind since time immemorial. Electricity too had been known since von Guericke's experiments in 1665 that showed charges could be created by friction. That there are two kinds of charges was shown by Dufay in France in 1733. Several electrostatic machines had been made since then. The Coulomb laws of electricity and magnetism were established (Priestley 1766, Cavendish 1771, Coulomb 1785) and with the work of Galvani (1780's) and Volta (1785) one could then have devices that made electricity flow. Still the interrelation between electricity and magnetism remained outside the scope of experiments. There were, of course, people who believed in interrelations between forces. The Danish scientist Hans Christian Oersted was one such person, who believed in the philosophy of Immanuel Kant and had expressed in 1806 that 'all power (light, electricity, heat and magnetism) are produced by the same power'. It took Oersted fourteen years to find physical evidence of the above 'naturphilosophie', and when he found it, scepticism appeared to have overtaken him. Oersted's experiment was as follows. He drove a current through a wire and kept a magnetic needle nearby enclosed in a glass box. There was no physical contact between the two. Before establishing the current the magnetic needle pointed in the north-south direction but once the current was established, the needle deflected and came to rest at a new position. What intrigued Oersted most was that the needle pointed in a direction, which was perpendicular both to the direction of the current as well as to the line joining the centre of the needle to the wire. If one described a circle round the wire (in the x-y plane), the direction of the magnetic needle followed the tangent to the circle (*Figure* 1). Later this was expressed mathematically as a law by Ampere and is known today as Ampere's law.

Figure 1. Magnetic field due to current in a straight wire. (Faraday traced the lines of force by sprinkling iron filings on a cardboard held perpendicular to the wire and found them to be denser in the wire's vicinity)



This was a kind of force that was not known before. If the needle was pulled towards or pushed away from the wire or had its north pole (or the south pole) pointing towards or away from the wire things would have been very satisfying. This was because scientists were familiar with what are called central forces, i.e.

forces that acted towards or away from certain points but this 'skew force' that Oersted saw went round an axis! It took Oersted four months to believe in what he saw and he finally said that it showed some 'conflicts' in the nature of electricity.

Stamps released in honour of Faraday and his work in UK.

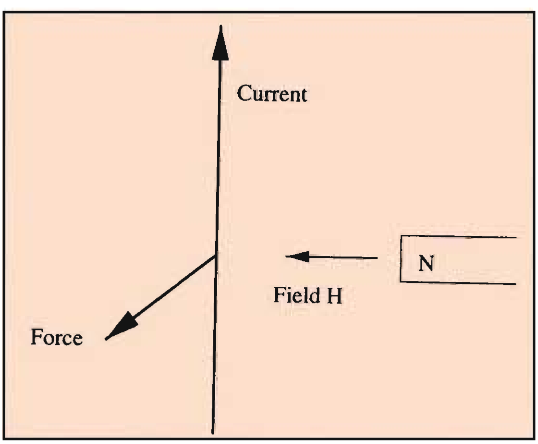
The person who immediately took off from Oersted's work was the French philosopher and natural scientist Andre Marie Ampere, whose seminal contribution would earn him such a wide recognition that he would be regarded as the 'Newton of electricity'. Ampere had no great interest in electricity before he heard about Oersted's discovery. He was a chemist and an atomist by conviction. He thought that deflection of magnetic needles by a current gave some idea about the arrangement of atoms and charges. To understand his approach, one must take a look at the picture scientists had of electromagnetism and atomism at that time. Ampere was initially a strong believer in Coulomb's idea of central forces and that electricity and magnetism were separate entities with no influence on each other. Skew forces discovered by Oersted put science in a dilemma. Ampere now suggested that magnetic properties of currents were actually of electrical origin. Just as Coulomb had shown that static charges could pull or push each other, so would moving charges. He proved this by a series of experiments. If wires carry currents in the same direction they repel, while if they carry currents in opposite directions, they attract each other. Ampere's results appeared in the 'Memoir on the mathematical theory of electrodynamic phenomena deduced solely from experiments', in which 'the laws of electrical action were expressed with elegance, economy and severe mathematical beauty'. One of the findings contained here is Ampere's law on the magnetic field produced by currents – the law which was much later given completeness by Maxwell's introduction of the displacement current. Concerning magnetic properties of currents, Ampere held the view that magnetic forces were the result of two electric fluids – which in permanent magnets went in circles – concentric to the axis of the magnet in a plane perpendicular to the axis. Attempts by Fresnel failed to detect these

Wires carry currents in the same direction they repel, while if they carry currents in opposite directions, they attract each other.

currents. Following Fresnel's suggestion, Ampere modified his views and suggested that these were not bulk currents but 'molecular currents'.

Faraday found these hypotheses a little obscure. His being mathematically illiterate produced no small difficulty, as he conceded to Ampere, 'with regard to your theory, it so soon becomes mathematical that it quickly gets beyond my reach'. But as a chemist this new mechanical picture of molecules and currents kept Faraday wondering as to what manifestations they could create. The same point was being debated by Davy. His friend William Wollaston had concluded that these circulating currents in molecules must give rise to a torque in a current carrying conductor when a magnet is brought close to it. They conducted several experiments in the Royal Institution and could not detect any rotational effects of currents. During the course of this work Davy never sought the help of his one-time trusted assistant Michael Faraday. Faraday too was a bit aloof from this work, being occupied with metallurgy, chemistry and with a romantic affair with his would-be bride Sarah Barnard.

Figure 2. Force on a current carrying conductor due to a magnetic field, H – this is called Fleming's left hand rule.



While working on his review in the summer of 1821, Faraday asked the question: What effect does a magnet produce on a current? This was also the question Davy and Wollaston asked. Faraday started with a simple experiment. He took a straight wire carrying current and brought a magnet near it holding it perpendicular to the direction of the current. The wire got deflected in a direction perpendicular to the direction of the current as also to the direction of the axis of the magnet (*Figure* 2). It was now clear that to rotate the wire one must choose a way by which the force could be enhanced, also if the torque could be large. The experiment Faraday chose to do was as follows.

A long bar magnet was stuck vertically with wax in a deep basin. The basin was filled with

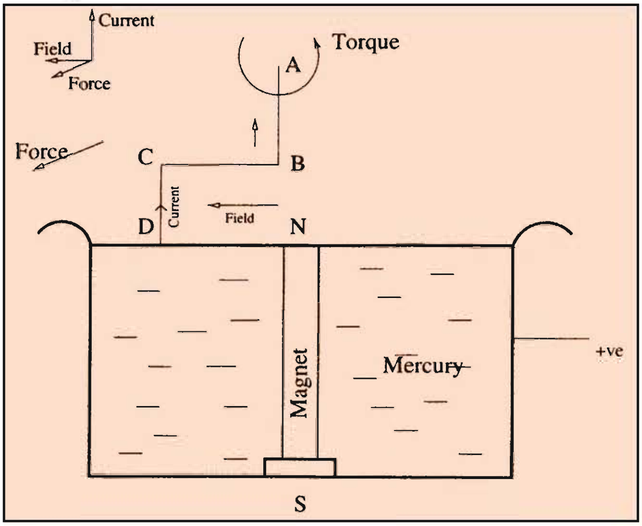


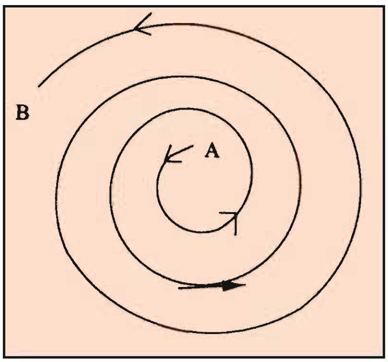
Figure 3. Experimental scheme to demonstrate "electromagnetic rotation".

mercury till the upper pole of the magnet was just about immersed in it. A wire was bent in the form of a frame ABCD as shown in *Figure* 3, with the lower tip D of the wire touching the surface of mercury. When current was passed through ABCD (by a voltaic pile), the wire frame rotated around the axis AB (*Figure* 3). The first electric motor had thus been made.

This experiment brought Faraday fame from all over Europe. The experiment was repeated in other places by many workers. Regrettably, 'infame' followed soon. Davy and Wollaston accused Faraday of stealing their ideas. In reality, however, neither Davy nor Wollaston had discussed their ideas with Faraday. It was indeed known that they were trying to find the 'electromagnetic' rotation but nothing more was revealed. Sensing their sensitivity to the issue, Faraday had tried to meet Wollaston before submitting the final version of the paper. But Wollaston was away. Faraday too, being conscious of the importance of priority, submitted the manuscript without waiting for Wollaston's comments. This infuriated Davy and Wollaston. Faraday had to face Davy's public reproach and in 1824, when Faraday's election to The Royal Society was being scrutinized, Davy gave the only dissenting vote.

Faraday continued to be preoccupied with the question of attraction of currents to each other and thought that magnetism had something to do with it. Here again he showed his ingenuity as an experimenter and an independent thinker. He took a flat spiral (*Figure* 4) and connected the points A and B to a battery. Current thus flowed in opposite directions around the point A. Iron filings were sprinkled on this spiral and it was found that they collected in heaps near the point A, i.e. the centre of the

Figure 4. Spiral, with the direction of current being indicated.



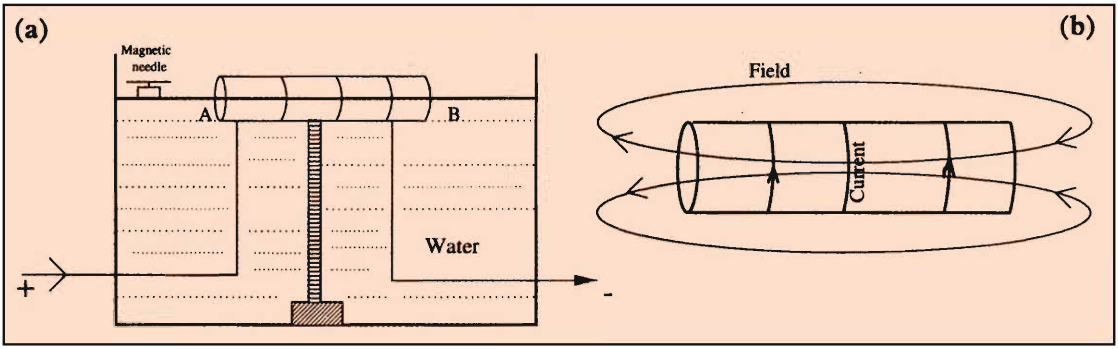
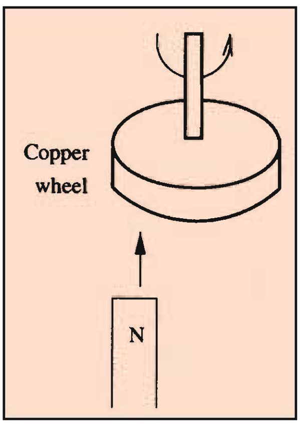


Figure 5. (a) Experimental arrangement to prove that magnetic lines of force are continuous.
(b) Magnetic lines of force (thin lines) produced by a current (thick lines with arrow) in a solenoid.

spiral. Faraday extended this experiment with a modified set-up that eventually gave a deep insight into the nature of magnetism and the question of lines of force.

Faraday wound an insulated wire around a glass tube 1 inch in diameter and 3 inches in length and fixed it in a flat basin (*Figure* 5a). The basin was next filled with water so that the level of water reached AB in the tube. A magnetic needle fixed in a cork was floated in the water. Then a current was established in the coil and it was observed that not only did the needle turn from its initial direction of pointing, it also started floating towards the tube indicating the existence of a force of attraction between it and the tube. This also happened if the needle was left under the influence of a magnet. The needle approached the open end of the tube facing it, and eventually entered the tube, crossed its length and emerged from the other end into the basin of water. In terms of the concept of lines of force it demonstrated that the lines are continuous and closed. They passed all along and did not end at the poles (*Figure* 5b). This experimental demonstration provided for a great conceptual advance in electromagnetism.

Figure 6. Scheme of Arago rotation experiment.

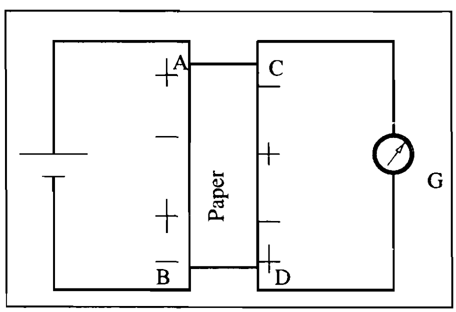


While these experiments kept Faraday busy, important events were taking place elsewhere too. Arago in France, Barlow and Christie in England discovered simultaneously what is known today as 'Arago rotation'. A copper disc (*Figure* 6), when spun rapidly close to a magnet, dragged the magnet along, while if the magnet were spun, it dragged the disc along. What surprised everyone was that even a non-magnetic substance like copper was getting magnetized! If a non-magnetic sheet of metal were placed between the magnet and the disk, the effect was unchanged but if an iron sheet was placed in between, the magnetic drag vanished. These experiments indeed showed the existence of electromagnetic induction and are due to what we call today 'eddy currents'. They also showed that magnetic lines of force could be screened by magnetic materials. This result triggered Faraday to try an experiment, which brought him close to the discovery of electromagnetic induction. The physics community had tried to explain Arago rotation in terms of changes in molecular electric currents that arose with the introduction of a magnetic field. But what could not be explained was what role the rotation of the wheel had in terms of changing these molecular currents.

Faraday was convinced of the existence of electromagnetic induction. He wrote in his diary: "If magnetic action be simply electrical action as *M*. Ampere considers it, then magnetic induction must be electrical induction and *M*. Arago's experiment must depend upon induced electric action."

Faraday was by then convinced of the existence of electromagnetic induction. He wrote in his diary: "If magnetic action be simply electrical action as *M*. Ampere considers it, then magnetic induction must be electrical induction and *M*. Arago's experiment must depend upon induced electric action." Ampere's theory provided the starting point of testing this hypothesis. According to Ampere matter got separated into positive and negative charges and they existed as separate entities for a short but finite time. Faraday made a device of the type shown in *Figure* 7. In his own words "Two copper wires were tied close together, a thickness of paper only intervening for a length of five feet." He passed current through one of the wires and tried to see the effect on the other neighbouring wire. If Ampere were correct, he argued, the separated charges must electrostatically induce charges in the other wire. Positive charges in the wire AB, as they move with the current, must drag along the negative charges in CD. There must be a current in CD. There was no current seen "though the galvanometer was not a delicate one", "no apparent effects were seen", noted Faraday.

Figure 7. Scheme of Faraday's 1825 experiment.



It was indeed accidental that Faraday did not try to

Faraday's diary gives the impression of a true natural philosopher whose interests ranged far and wide and one who was ever ready to perform experiments to see and verify different phenomena.

see the effect by turning the current on and off. This he did six years later, in 1831 and thus the discovery of electromagnetic induction had to wait.

In the intervening years Faraday's interest drifted to acoustics. What inspired him most was that the mechanical vibrations in sound could be seen on a screen. Wheatstone had done this and demonstrated it in many of his lectures. Sound was thus a wave. Faraday was also inspired by the work of Fresnel and Young who had proved the wave nature of light through their experiments. Faraday saw a connection between light and sound, since both were waves. It may be worthwhile to describe one of the experiments on sound that Faraday did at that time. He placed a glass jar on a metal plate and partially evacuated the jar. The plate could be covered with any material, e.g., even liquids, including some very viscous ones like the white of an egg. On setting up a vibration of the plate, it was seen that the vibration was picked up by the liquid. The remarkable thing he noticed was that the effect was immediate. One had to look at things that took place very fast. This he would now do in electromagnetism.

During the months of February and March of 1831 Faraday was still working on acoustics. In April of that year, he wrote in his diary about 'An Aurora seen at Woolwich'. On May 30 of the same year there is a diary entry on thermoelectric effect. In June and July he observed crispations and ridges on sand at Hastings. In mid-August he experimented on copper-plate printing and on spontaneous ignition of hot vapours. His diary gives the impression of a true natural philosopher whose interests ranged far and wide and one who was ever ready to perform experiments to see and verify different phenomena. The discovery of electromagnetic induction took place through a series of experiments that he conducted from August 29 to November 4, 1831. The discovery was facilitated by a letter from his friend Gerritt Moll of Utrecht. Moll had found that on changing the direction of current, electromagnets changed their polarity and also that the strength of an electromagnet could be enhanced enormously by putting some magnetic material like iron inside. This set

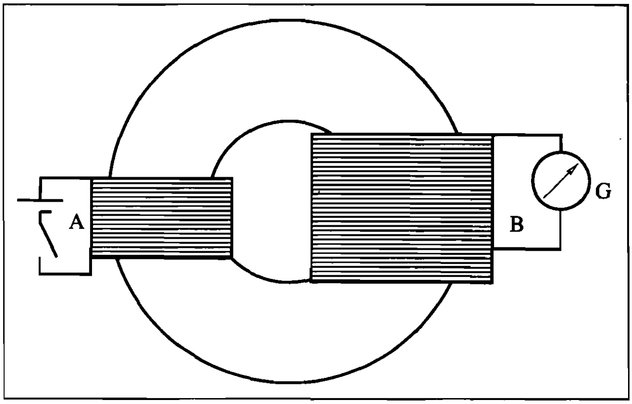


Figure 8. Scheme of Faraday's 1831 experiment, which established electromagnetic induction.

Faraday thinking. He now modified his 1825 experiment. He produced a coil of the type shown in *Figure* 8. In his diary he wrote "Have an iron ring made, iron round and 7/8 inches thick and the ring 6 inches in external diameter. Wound many coils of copper wire round one half, the coils being separated by twine and calico. There were 3 lengths of wire each about 24 feet long and they could be connected as one length or used as separate lengths. ... Will call this side of the ring A. On the other side but separated by an interval was wound wire in two pieces together amounting to about 60 feet in length, the direction being as with the former coils; this side call B". What made this experiment different from the 1825 experiment was that Faraday was no longer looking for continuous effects but transient ones or wave-like ones. He had realised that the current had to be turned on and off. What he did and saw are given below in his own words: *"Connected the ends of one of the pieces on A side with battery; immediately a sensible effect on the needle. It oscillated and settled at last in original position. On breaking connection of A side with battery again a disturbance of the needle ... Continued the contact of A side with battery but broke and closed alternately contact of B side. No effect at such times on the needle – depends upon the change in the battery side. Hence is no permanent or peculiar state of wire from B but effect due to a wave of electricity caused at moments of breaking and completing contacts at A side."* The phenomenon of electromagnetic induction was thus firmly established.

Faraday has two units named after him, a unique honour indeed. The first most commonly used is 'farad' the unit of capacitance and then there is 'faraday' which is a unit of charge.

Nearly simultaneously, a school teacher from Albany in the USA, by name Joseph Henry, also reported the discovery of electromagnetic induction. The unit of inductance is named after him while Faraday has two units named after him, a unique honour indeed. The first most commonly used is 'farad' the unit of capacitance and then there is 'faraday', which is a unit of

Thomson showed that lines of force could be used to explain the mathematical theory of electrostatic action. This approach was brought to completion by James Clark Maxwell in 1855. Maxwell used Faraday's concepts about changing magnetic flux to lay the foundations of a complete theory of electromagnetism.

charge. The discovery of electromagnetic induction established the connection between dynamic magnetic flux and the *emf* generated by it. However, it did not have a mathematical theory. The theory needed a new kind of concept, the question of the electromagnetic field, and also the question of lines of force. Faraday introduced these concepts at various times between 1822 and 1836 but they remained unacceptable to the community of physicists during Faraday's time. On November 24, 1831 Faraday read his paper on electromagnetic induction to the august audience at The Royal Society. Soon after he left for a holiday in Brighton.

By January 1832 the concept of an electromagnetic field had taken firm roots in Faraday's mind. Two months later he wrote:

"When a magnet acts upon a distant magnet or a piece of iron, the influencing cause ... proceeds gradually from magnetic bodies, and requires time for its transmission which will probably be found to be very sensible. I think also that I see reason for supporting that electric induction (of tension) is also performed in a similar progressive way."

The first support of Faraday's field concept came from William Thomson, later Lord Kelvin. Thomson showed that lines of force could be used to explain the mathematical theory of electrostatic action. This approach was brought to completion by James Clark Maxwell in 1855. Maxwell used Faraday's concepts about changing magnetic flux to lay the foundations of a complete theory of electromagnetism. About the special trait of Faraday's method this is what Maxwell had to say:

"Faraday in his mind's eye, saw lines of force traversing all space where the mathematician saw centres of force attracting at a distance. Faraday saw a medium where they saw nothing but a distance. Faraday sought the seat of phenomena in real action going on in the medium, they were satisfied that they had found it in a power of action at a distance impressed on the electric fluids. When I had translated what I considered to be Faraday's ideas into a mathematical form, I found that, in general, the results of the two methods coincided ... but that....several of the most fertile methods of research discovered by the

mathematicians could be expressed much better in terms of the ideas derived from Faraday than in their original form."

The practical importance of Faraday's discovery of electromagnetic induction hardly needs an elaboration today as the century just gone by was rightly described by J D Bernal as the 'century of electrical sciences'. However, the first commercial generation of electricity by generators took place only in 1881 after Edison's work on power stations. Electric lighting of the streets of London became an impetus for the generation of electricity, but only after the electric industry could win some decisive battles against the gas industry. As Bernal says, Faraday was well aware of these obstacles and had thus "little inclination to move in the direction of practical applications. This was not due to any other worldliness; Faraday knew enough from experience of the world of business and government to estimate the time and trouble it would take to bring any of his ideas to the stage of profitable exploitation." He felt he could make better use of his time through discourse. As a public figure Faraday drew large audiences at the Royal Institution (over a hundred lectures between 1825 and 1862). He was a committed science populariser and gave 19 Christmas lectures to children and an aggregate of 85,000 children would have listened to him, – an enormous number – considering that they were given in the pre-TV age! He considered it a duty to remind the society of the importance of "*men who can teach and that class had to be created*". And as regards education, Faraday considered that "education must teach self-education and self-criticism. This education has for its first and its last step humility." True to what he preached, he lived without official decorations from governments or from the British Crown. His epitaph reads:

MICHAEL FARADAY
Born 22 September 1791
Died 25 August 1867.

"*He had remained simple Mr. Faraday to the end*".

Suggested Reading

[1] L Pearce Williams, *Michael Faraday*, Chapman and Hall, London 1965.

[2] John Meurig Thomas, *Michael Faraday and the Royal Institution: The Genius of Man and Place*, Adam Hilger, Bristol, 1991.

[3] Nersessian Nancy J, in *Faraday Rediscovered*, Ed. David Gooding and Frank A J L James, M Stockton Press, 1985

[4] J D Bernal, *Science in History*, Vol. 3, Pelican, Harmondsworth, 1969.

Address for Correspondence
S Chatterjee
Indian Institute of Astrophysics
Bangalore 560 034, India.
Email: chat@bgl.vsnl.net.in, chat@iiap.ernet.in