europhysics news

BULLETIN OF THE EUROPEAN PHYSICAL SOCIETY

J.A. Volume 10 Number 12 December 1979

James Clerk-Maxwell: A View from the 20th Century

Cyril Domb, London

(Clerk-Maxwell Professor of Theoretical Physics, King's College)

When James Clerk-Maxwell died on 5 November, 1879 at the early age of 48, he was certainly regarded as a scientist of great distinction. Others of his contemporaries, however, would probably have been given a higher rating, perhaps Faraday or Kelvin or Helmholtz. In the century which has passed, Maxwell's prestige has steadily risen until now he is on a pinnacle with Newton and Einstein as one of those fundamental thinkers of the scientific era who have changed our whole picture of the physical world. In fact it was Einstein who described the change in conception of *Reality* in physics after Maxwell as "the most fruitful that physics has experienced since the time of Newton". The only portraits in Einstein's study were of Newton, Faraday and Maxwell.

Although Maxwell lived in the 19th century, his thought belonged to the 20th century. His concept of electromagnetic radiation and his field equations paved the way for the special theory of relativity, and hence for the famous Einstein relations between mass and energy. The other major innovation of 20th century physics, the quantum theory, also leaned heavily on Maxwell's ideas. It was only after Maxwell that one could introduce the concept of black body radiation, and worry about the ultra-violet catastrophe of the classical theory with an infinite amount of energy in radiation of short wavelengths. In trying to remove this catastrophe, Planck was led to introduce his quantum hypothesis; and the interaction between electromagnatic radiation and matter has played a central role in the development of the theory of the structure of atoms and molecules.

Thermodynamics and the Gas Laws

Besides his outstanding work on electromagnetic theory, Maxwell made major contributions to other branches of physics. In thermodynamics, the Maxwell relations are part of the standard content of every textbook, and represent one of the simplest and most useful applications of the second law. Whilst Clausius in his 1857 paper laid the foundation of the modern

Fig. 1 — James Clerk-Maxwell in his later years (from a portrait at King's College, London).

Kinetic Theory of Gases, it was Maxwell who saw clearly that the methods of probability and statistics must be used in describing the properties of an assembly of molecules; in 1859 he put forward his famous formula for the distribution of velocities in an ideal gas, and even though his arguments were inadequate, his remarkable physical intuition ensured that the result was correct.

In later papers, Maxwell investigated the transport properties of gases, i.e. the behaviour of viscosity, thermal conductivity and diffusion with change of temperature and pressure. He concluded from his calculations that the viscosity of a gas should be independent of pressure, and proceeded

Fig. 2 — Extract from Maxwell's 1862 paper in the Philosophical Magazine in which he first formulated the electromagnetic theory of light.

ON PHYSICAL LINES OF FORCE.

The velocity of light in air, as determined by M. Fizeau*, is 70,843 leagues per second (25 leagues to a degree) which gives

V = 314,858,000,000 millimetres

= 195,647 miles per second .... (137).

The velocity of transverse undulations in our hypothetical medium, calculated from the electro-magnetic experiments of MM. Kohlrausch and Weber, agrees so exactly with the velocity of light calculated from the optical experiments of M. Fizeau, that we can scarcely avoid the inference that *light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena.*

Contents

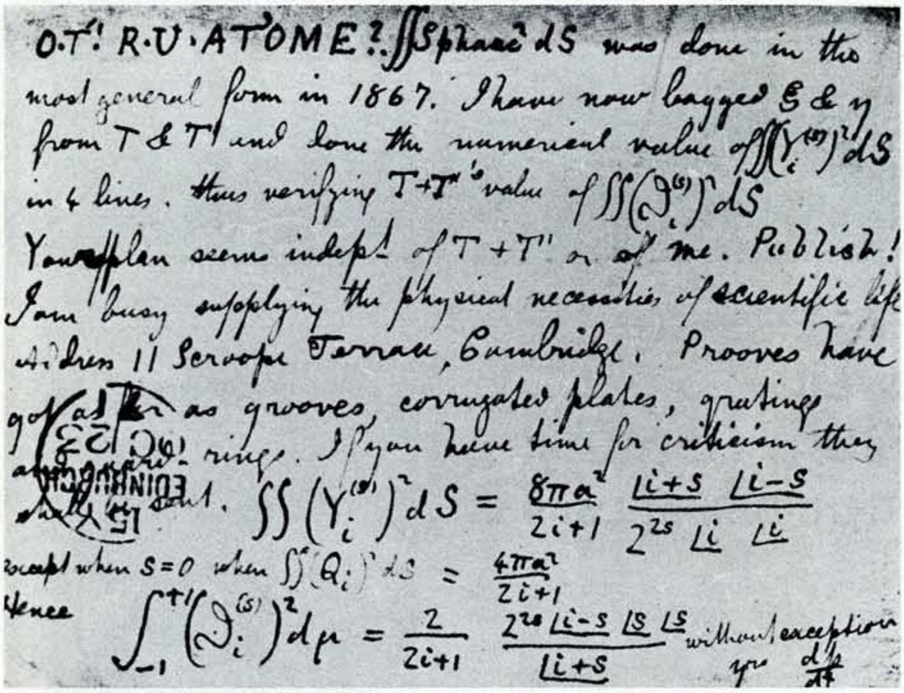
O.T.! R.U. ATOME?. ∬Sphaae dS was done in the
most general form in 1867. I have now bagged ξ & η
from T & T' and done the numerical value of $\iint (Y_i^{(s)})^2 dS$
in 4 lines. thus verifying T+T' value of $\iint (Q_i^{(s)})^2 dS$
Your plan seems indep^t of T+T' or of me. Publish!
I am busy supplying the physical necessities of scientific life
Address 11 Scroope Terrace, Cambridge. Prooves have
got as far as grooves, corrugated plates, gratings
and ... rings. If you have time for criticism they
$$\iint (Y_i^{(s)})^2 dS = \frac{8\pi a^2}{2i+1} \frac{|i+s \; |i-s}{2^{2s} \; |i \; |i}$$
except when s=0 when $\iint (Q_i)^2 dS = \frac{4\pi a^2}{2i+1}$
Hence
$$\int_{-1}^{+1} (Q_i^{(s)})^2 d\mu = \frac{2}{2i+1} \frac{2^{2s} \; |i-s \; |s \; |s}{|i+s}$$ without exception
yrs $\frac{dp}{dT}$

Fig. 3 — One of the postcards sent by Maxwell to his friend P. G. Tait. William Thomson (Lord Kelvin) is denoted by T, P. G. Tait by T', and Maxwell signs himself dp/dT in accordance with the thermodynamic relation dp/dT = JCM. The term T and T' used in lines 3 and 4 refers to the famous 19th century text by Thomson and Tait, Elements of Natural Philosophy *(reproduced by kind permission of the Syndics of Cambridge University Library).*

to test this result experimentally. He noted that a particular simplification in the calculations occurs for molecules interacting with a repulsive force inversely proportional to the fifth power of their distance apart, and this molecular model seemed to fit his experimental results. In the last major paper of his life published in 1879, he laid the foundations of the theory of rarefied gas dynamics.

Interest in Colour

It will be seen from the above that Maxwell was far from being an abstruse theoretician. He was skilful in the design of experimental apparatus, as was shown early in his career in investigations of colour vision. He devised a colour top to test the three primary colour hypothesis of Thomas Young, and later invented a colour box to enable experiments to be made with spectral colours rather than pigments. Although some of his work was paralleled by Helmholtz, it was he who made the crucial observation that Young's hypothesis works only if negative as well as positive contributions are allowed.

From the three-colour theory, Maxwell concluded that by photographing through filters of three different colours and then recombining the images, it should be possible to make a colour photograph of any object. He demonstrated this practically in a lecture to the Royal Institution in 1861 by photographing a tartan ribbon by a method substantially the same as is used nowadays.

On the theoretical side, his mastery of classical physics was demonstrated when he was still young in his investigation of the constitution of Saturn's rings, described by Airy as one of the most remarkable applications of mathematics he had ever seen.

Maxwell's Originality

In 1871 Maxwell published an excellent textbook entitled *Theory of Heat.* Near the end, to demonstrate the statistical character of the Second Law of Thermodynamics, he introduced his famous demon which was a hypothetical being who could follow the path of every molecule. By suitably opening and closing a trapdoor the demon could get round the Second Law. The suggestion intrigued many distinguished scientists in subsequent years including Kelvin, Smoluchowski, Szilard and Brillouin. The demon thus acted as a catalyst in promoting a mathematical theory of information in which information is interpreted as negative entropy. Only then did it become clear that such a demon cannot function and that the second law remains sacrosanct.

In a paper published in 1868, Maxwell provided the first analytic treatment of governors, devices which ensure that the velocity of a machine remains nearly uniform despite variations in driving power or resistance. He derived and solved differential equations for the motion introducing a term later to be characterized as negative feedback; this paper laid the foundation of control theory, known nowadays as cybernetics.

Whilst still a student at Cambridge in 1853, Maxwell undertook a study in geometrical optics "suggested by the contemplation of the structure of the crystalline lens in fish". He arrived at a mathematical description of a medium in which focussing would be perfect. Nearly a century elapsed before Luneburg revived the subject and found other instances of perfect imaging devices. From his earliest years Maxwell had been fascinated by geometry, and several of his papers are concerned with a geometrical approach to problems in mechanics and physics.

An example of the casual way in which Maxwell produced original ideas is provided by the theory of the propagation of light in a dispersive medium. A formula for the refractive index was put forward by Sellmeyer in 1871. Twenty years after Maxwell's death Rayleigh pointed out that Maxwell had derived the same formula in 1869 in a question set in the Mathematical Tripos exam at Cambridge!

Maxwell was always alert to the work of scientists in other countries. When van der Waals published his doctoral thesis in 1873, Maxwell made the effort of learning Dutch to be able to study it. He publicised it to the English speaking world by means of a review in *Nature* in 1874 and a lecture to the Chemical Society in 1875 where he supplied the important "Maxwell construction" missing in the van der Waals' treatment. Likewise in the 1870's he drew attention to the power of the new thermodynamic methods introduced by William Gibbs, and moulded in plaster of Paris, a Gibbs surface for a substance satisfying van der Waals' equation.

A particularly striking demonstration of his physical intuition is provided by his criticism of the calculation by the kinetic theory of gases, of γ (the ratio c_p/c_v) for gases of diatomic molecules. The largest possible value a model calculation could give was 1.33, but experimental values for several gases were found to be 1.408. Maxwell stated in a lecture in 1875: "I have now put before you what I consider to be the greatest difficulty yet encountered by the molecular theory". He dismissed an attempt by Boltzmann to take account of the motion of the ether as making matters even worse. The difficulty was resolved only when Planck's quantum hypothesis led to the phenomena of frozen modes at low temperatures.

Biographical Notes

We end this brief summary with a few biographical and historical notes. Maxwell was born in Edinburgh in 1831 into a comfortable middle class family, which almost immediately moved into a country house in the estate which his father had inherited. He went to the Edinburgh Academy School from 1841-47 and then to Edinburgh University from 1847-50 ; it was here that his interest in colour vision was first aroused. Proceeding to Cambridge in 1850 his unusual talents began to be recognized ; he was second wrangler and first Smith's prizeman in 1854 and was elected to a Fellowship at Trinity College in 1855. In 1856 he left to take up an appointment as Professor of Natural Philosophy in Marischal College, Aberdeen. His most important publication during the Cambridge period was a paper of 75 pages "On Faraday's Lines of Force". He spent four years at Aberdeen during which he won the Adams Prize for his work on Saturn's rings. In 1858 he married Katherine Mary Dewar, daughter of the Principal of the College ; there were no children.

In 1860 he moved to King's College, London. The five years which he spent there were the most fruitful of his life, and saw the publication in 1861-2 and 1864 of his pioneering classic papers on the electromagnetic field. In addition he supervised the experimental determination of electrical units for a British Association Committee. In 1865 he resigned his Chair at King's and retired to the family home in Glenlair, Scotland. Much of his time and energy was now devoted to the planning and writing of his treatise on Electricity and Magnetism.

Maxwell emerged from retirement in 1871 to take up the newly established Chair in Experimental Physics at Cambridge. During the final years of his life he initiated the great Cavendish Laboratory tradition which was implemented by his successors Rayleigh, J.J. Thomson, Rutherford, Bragg, Mott and Pippard. His students, few in number, but of the highest quality, included Niven, Ambrose Fleming, Glazebrook, Poynting, and Schuster.

If one turns to any page at random in Maxwell's collected works one is likely to find a feature of novelty and interest. In the words of the late Charles Coulson, "there is scarcely a single topic that he touched upon which he did not change almost beyond recognition".

JET — Not Just a Technical Challenge

Western Europe's Joint European Torus experiment for studying the tokamak configuration under near reactor conditions is a pioneering operation not only in science but also in organizational terms. A new approach to international development is required that can envisage application as well as research.

Cranes, bulldozers and excavations in the field alongside, and a group of black and white temporary buildings next the football pitch, mark the presence of the Joint European Torus project at the U.K. Atomic Energy Authority's site at Culham. The hopes and plans of so many years are now being translated into concrete terms and Europe's largest tokamak will soon begin to take shape.

Despite its uniqueness as the first Joint Undertaking to be set up under the European Communities, JET suffers in more than one way from being tied to atomic energy structures that have aged under the effects of many years of frustrating work.

In the fifties, the new technology of nuclear power brought together the most innovative and energetic scientists and engineers of their day; thirty years and many disappointments later, it is not easy to recapture that pioneering drive, particularly when recruitment in so many organizations has stood still and the younger men have gone elsewhere. A major problem for JET is building a team that has all the fire and inventiveness of the old days — or rather of the new days — particularly in regard to engineering; physicists of quality are more easy to come by but their rôle at the moment is less crucial than that of the engineers. JET, at this juncture, is primarily an engineering experiment, where the goal is to build a device that will confine and heat plasma to near reactor temperatures. In the experimental programme which follows completion of construction, the physicist will come back into his own. Nevertheless, it must be recalled that JET has the explicit purpose of furthering the techniques for achieving economic power generation. There is no spare effort within the joint programme for plasma physics research for its own sake; that has to be funded from other sources.

It is of course logical that thermonuclear fusion should be seen as a section of nuclear power development, partly because historically it developed as an adjunct to fission, partly because many of the technical problems such as fast neutron fluxes and a radioactive environment are similar to the problems met in fission. The bond may even become stronger in the future, as some authorities are suggesting that the main use of D-T fusion reactors, at least in the initial stages, will be to produce fissile material for a fusion-fission cycle. The days are gone when fusion is publicized as offering in the near term, clean, illimitless power from the sea. Instead, there is a more sober awareness of the difficulties of getting even the D-T reaction to work and then transforming the energy efficiently into a transportable form.

On the technical side, fusion has inherited the rigorous scientific tradition and the high quality engineeing standards of fission to its advantage, but at the same time it suffers from being enmeshed in organizations that were created before the magnitude and complexity of the research, development, industrialization problem were understood and when these three processes tended to continue as separate and independent activities. International cooperation at the research stage was not unknown in fission but it rarely carried over into the development phase.

Collaboration in fusion has been going on quietly over the past two decades. JET, however is something new, going beyond the liaison between individual departments that has characterized fusion research in western Europe to date. As such it will require a new orientation of priorities that can adapt to a progressive advance on a common front through to industrialization — a process which, every bit as much as research, should be seen as requiring an international approach.

Funding

Viewed against the public agonising over energy sources, funding of JET, totalling 184.6 M EUA at January 1977 prices for the 5-year so-called construction phase, has not been particularly generous, and provision for indexing the budget to allow for price escalations was not made automatic. As such, the international supervisory bodies can easily find themselves in the invidious position of trying to

The value of the EUA varies but is currently the equivalent of about 2.3 Sw.Fr.