BIOGRAPHICAL MEMOIRS OF FELLOWS OF THE ROYAL SOCIETY

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H.K. Moffatt

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Elected F.R.S. 1957

BY H.K. MOFFATT, F.R.S.

Department of Applied Mathematics and Theoretical Physics,
The University of Cambridge, Silver Street, Cambridge CB3 9EW, UK

George Batchelor was a pioneering figure in two branches of fluid dynamics: turbulence, in which he became a world leader over the 15 years from 1945 to 1960; and suspension mechanics (or 'microhydrodynamics'), which developed under his initial impetus and continuing guidance throughout the 1970s and 1980s. He also exerted great influence in establishing a universally admired standard of publication in fluid dynamics through his role as founder Editor of the *Journal of Fluid Mechanics*, the leading journal of the subject, which he edited continuously over four decades. His famous textbook, *An introduction to fluid dynamics*, first published in 1967, showed the hand of a great master of the subject. Together with D. Küchemann, F.R.S., he established in 1964 the European Mechanics Committee (forerunner of the present European Society for Mechanics), which over the 24-year period of his chairmanship supervised the organization of no fewer than 230 European Mechanics Colloquia spanning the whole field of fluid and solid mechanics; while within Cambridge, where he was a Fellow of Trinity College and successively Lecturer, Reader and Professor of Applied Mathematics, he was an extraordinarily effective Head of the Department of Applied Mathematics and Theoretical Physics from its foundation in 1959 until his retirement in 1983.

AUSTRALIAN ROOTS

George Keith Batchelor was born in Melbourne, Australia, on 8 March 1920. His Australian roots went back three generations to his great-grandfather, David Scott Batchelor, a joiner from Broughty Ferry, Scotland, who had emigrated in 1852 to Australia to work on the Catholic Cathedral in Melbourne. George's grandfather was a Methodist lay preacher and a wholesale distributor of books and magazines in Melbourne. His father, George Conybere Batchelor (1897–1985), fought with the Australian overseas contingent in France during World War I; in 1918 in London he married Ivy Constance Berneye (1899–1943), daughter of a journeyman silversmith (who was himself the son of a jeweller/silversmith originally from Bratislava), and returned with her to Australia in 1919.

George had one younger sister, Doris, born in 1928, for whom he filled the role of the protecting older brother. From 1929, the family lived at 107 Eglinton Street, Moonee Ponds, a suburb of Melbourne; this was George's home until his departure for England in 1945. After two years (1929–30) at Moonee Ponds West State School, he attended the nearest state secondary school, Essendon High School, for four years. He then went to Melbourne Boys' High School, where he studied mathematics, physics and chemistry, gaining entry to the University of Melbourne in March 1937. He enjoyed cycling, scouting and rowing on the River Yarra, and was a fan of Don Bradman, already a star in Australian cricket. He was a keen member of the YMCA, where he took part in debates and sporting activities and acquired leadership skills. During his schooldays he developed a fierce ambition to succeed in science and to play a leadership role in the scientific career that lay ahead of him. His childhood, no doubt influenced by his Methodist grandfather, was one of thrift, hard work and self-improvement. George's father remarried in 1946 and in 1949 had a daughter, Anne, step-sister to George.

Batchelor studied pure and applied mathematics and physics at Melbourne University, graduating in 1939. It was his hope to come to Cambridge to study for a PhD, and he was awarded the Aitchison Travelling Scholarship, which would, in normal circumstances, have made this possible. However, circumstances were far from normal: the eruption of World War II in September 1939 forced him to postpone such plans and to consider research possibilities in Australia. He was advised by Dr Eric Burhop (F.R.S. 1963), a theoretical physicist then at the University of Melbourne, that nuclear physics, to which he was initially attracted, had no foreseen useful applications (a remarkably non-prescient view), and that he should instead consider research in aeronautics, of great current relevance for Australia's embryonic aircraft production industry. Batchelor visited the Commonwealth Scientific & Industrial Research Organisation Division of Aeronautics and was taken on by Gordon Patterson (later Director of the Institute of Aerospace Studies at the University of Toronto) to undertake research for the MSc degree. His research project was to calculate the effect of the walls of a wind tunnel of octagonal cross-section on the lift and drag forces on models mounted in the tunnel. Batchelor duly graduated MSc with first-class honours in 1941, and joined the staff of the Division of Aeronautics as a Research Officer, a position that he held for the next four years.

It was during these four years that Batchelor's interest in fundamental fluid dynamics was aroused. He read such books on aerodynamics as were then available, and he studied the famous series of papers on the statistical theory of turbulence by Sir Geoffrey Taylor, F.R.S. (Taylor 1935, 1936); these convinced him that research into turbulence, then as now the most challenging branch of fluid dynamics, was what he wished to pursue. With remarkable assurance, he wrote to Sir Geoffrey (known to everyone in the world of fluid mechanics simply as 'G.I.') asking whether he would take him on as a research student when the war ended. G.I.'s positive reply made Batchelor very happy; his encouragement at this critical stage was of vital importance. G.I. recognized Batchelor's unusual talent and motivation through his early wartime correspondence with him; at the same time, Batchelor developed a profound respect for G.I., a respect that over subsequent years evolved into a deep affection and admiration, transparent in his biography *The life and legacy of G.I. Taylor* published half a century later in 1996 (see also his Biographical Memoir of Taylor) (20, 25)*.

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

One of Batchelor's young colleagues at the Division of Aeronautics was Alan Townsend (F.R.S. 1960), who had studied nuclear physics in Cambridge before the war and intended to return to complete his graduate studies when the war ended. Batchelor convinced Townsend of the challenge of the problem of turbulence (Townsend 1990), with the result that he also enrolled to work under Taylor in Cambridge; the ensuing partnership of Batchelor and Townsend, combining brilliance in both theory and experiment, and under the benign and inspired influence of Taylor, was to flourish for the next 15 years, during which the foundations of modern research in turbulence were to be established.

In January 1944, George married Wilma Rätz (1918–97), who trained as a social worker at the University of Melbourne; she was later to play an important role in her work for the Cambridgeshire Mental Welfare Association, for which she was in 1982 awarded the M.B.E. Three daughters were born of the marriage: Adrienne (1947), Clare (1950) and Bryony (1953).

In January 1945, George and Wilma were granted passage to England on the *Umgeni*, a cargo ship of about 6000 tons. Many of their fellow-passengers were women and children released from captivity under the Japanese and now allowed to travel home to Britain. The voyage lasted 10 weeks, via New Zealand, the Panama Canal, Jamaica and New York, then in a convoy of about 80 ships across the Atlantic to Tilbury docks in London. From there George and Wilma travelled to Cambridge, where they were destined to spend the rest of their lives. They gave the name 'Cobbers' to their eventual home in Cambridge, meaning 'companions' in Australian English, and made regular visits back to Australia over the decades that followed. The design of Cobbers, in the beautifully wooded Conduit Head Road in West Cambridge, was closely supervised by George, who paid meticulous attention to architectural details, even extending to a calculation (11) of the optimal spacing of the panes of glass for the double glazing—still then an unusual feature of homes in England. Cobbers was a happy home, and provided a congenial setting for the Fluid Dynamics parties at which the Batchelors would regularly welcome new research students and visitors to the Department of Applied Mathematics and Theoretical Physics (DAMTP) (see below).

Initial work on turbulence

Batchelor's initial encounter with G.I. Taylor must have been a little disconcerting, because it transpired that G.I. himself did not intend to work on turbulence, but rather to continue to work on a range of problems—for example the rise of large bubbles from underwater explosions, or the blast wave from a point release of energy—that he had encountered through war-related research activity. He was happy to give Batchelor freedom to develop his own programme of research, a strategy that worked well because Batchelor had in any case a fiercely independent streak. G.I. was to exert what seems to have been a father-figure influence, being available to provide critical comment but otherwise remaining quite detached from the turbulence research. Taylor and Batchelor published only one joint paper, 'The effect of wire gauze on small disturbances in a uniform stream' (3); apart from this, they pursued different research paths, with only occasional intersections.

Batchelor had been admitted as a Research Student at Trinity College, Cambridge (of which G.I. was himself a Fellow), to read for a PhD. From 1946 he was supported financially as a 'Senior Student of the Royal Commission for the Exhibition of 1851'. He relished the intellectual freedom that research-student status gave him, and in later life would look back on this time as one of his happiest periods. He always described research students as the 'princes' of the academic community, a view that undoubtedly derived from his own experience in the early postwar years. It is significant that, during his retirement many years later, through a donation to the college he initiated a fund to provide grants for graduate students coming to Trinity from the University of Melbourne.

Having settled in Cambridge, Batchelor lost no time in reading all the papers on turbulence that he could find in the library of the Cambridge Philosophical Society, where a huge collection of scientific journals was held. There he came upon the English-language editions of the 1941 volumes of *Doklady*, the *Comptes Rendus of the USSR Academy of Sciences*, in which the seminal papers of Kolmogorov (1941*a*,*b*) had been published; Batchelor immediately recognized the significance of these papers. In his lecture 'Fifty years with fluid mechanics' at the 11th Australasian Fluid Mechanics Conference (24), he said, 'Like a prospector systematically going through a load of crushed rock, I suddenly came across two short articles, each of about four pages in length, whose quality was immediately clear'. Four pages was the normal limit of length imposed by the USSR Academy for papers in *Doklady*, a limit that perhaps suited Kolmogorov's minimalist style of presentation, but at the same time made it exceptionally difficult for others to understand the implications of his work. Batchelor did understand these implications, and proceeded to a full and thorough discussion of the theory in a style that was to become his hallmark: the assumptions of the theory were set out with the utmost care, each hypothesis being subjected to critical discussion both as to its validity and its limitations; the consequences were then derived, and illuminated with a penetrating physical interpretation at each stage of the argument.

The resulting 27-page paper (2) was published in the *Proceedings of the Cambridge Philosophical Society* in 1947. Batchelor had earlier announced some of his findings at the 6th International Congress of Applied Mechanics (1) held (remarkably) in Paris in September 1946, when he also drew attention to the parallel lines of enquiry of Onsager, Heisenberg and von Weizsäcker. There is an interesting historical footnote to this: both Heisenberg and von Weizsäcker had been taken, together with other German theoretical physicists, to Britain at the end of the war with Germany, and placed under house arrest in a large country house, the now famous Farm Hall, not far from Cambridge. G.I. Taylor visited them (probably in August 1945 (24)) to discuss energy transfer in turbulent flow but it was only after the visit, as a result of a conversation with Batchelor, that G.I. recognized the link with Kolmogorov's work. As Batchelor said, 'The clearest formulation of the ideas was that of Kolmogorov, and it was also more precise and more general'. There can certainly be little doubt that it was Batchelor's 1947 paper (2) that effectively disseminated the Kolmogorov theory to the Western world. Akiva Yaglom, a former student of Kolmogorov's, has told me that, in Russian translation, it also served to make the theory comprehensible to turbulence researchers in the Soviet Union (see also Barenblatt 2001). Over the following years, Batchelor was to be increasingly preoccupied with exploiting the new insights that the Kolmogorov theory provided in a range of problems, including the problem of turbulent diffusion, in which the small-scale ingredients of the turbulence have a key role.

Largely on the basis of his work on Kolmogorov's theory, Batchelor was elected to a Research Fellowship at Trinity College in October 1947. This gave him the wonderful opportunity to pursue his research for a further four years, freed from other commitments. As a research fellow of the college, he had the opportunity to supplement his income by college teaching, which he did for a brief period. For the most part, however, he devoted himself with great intensity to research, considering that the weekly supervision of undergraduates, one or two at a time, was a misuse of valuable time. Before the expiry of his fellowship in 1951, Batchelor had already published more than 15 substantial papers on many aspects of turbulent flow. His achievement was such that, with the backing of G.I., he was re-elected to a senior ('Title B') Research Fellowship, a rare distinction within the college, and a position that he held until, on his election in 1964 to the newly created University Chair of Applied Mathematics, it was automatically converted to a Professorial Fellowship.

In parallel with the Trinity Fellowship, Batchelor was appointed to a lectureship in the Faculty of Mathematics in 1948. He developed courses in fluid dynamics at both undergraduate and graduate (Part III) level, drawing inspiration more from the approach of Prandtl (in his *Essentials of fluid dynamics*) than from the more traditional texts of Lamb and Milne-Thomson; Batchelor's fluid dynamics was very firmly based on real fluids endowed with viscosity from the start, and the 'classical' potential theory of inviscid flow was postponed in his teaching until at least the elements of boundary-layer theory were understood. This approach, developed over many years and tested on successive generations of Cambridge mathematics students, was to form the basis of Batchelor's famous textbook *An introduction to fluid dynamics* (15), published by Cambridge University Press in 1967, a book that has taken its place, alongside Lamb's *Hydrodynamics*, as one of the classic texts of the subject.

Turbulence in the 1950s

The ideas of homogeneity and isotropy (i.e. invariance of statistical properties of a field of turbulence under translations and rotations) had been introduced by G.I. Taylor in the 1930s, but it was Batchelor who, during his early years in Cambridge, pursued these concepts with great thoroughness and exploited them to the full. His work of that period is summarized in his Research Monograph *The theory of homogeneous turbulence* (10), published by Cambridge University Press in 1953. This small book opened up a new field of research and was immensely influential over at least the next two decades. It was republished as a Cambridge Classic in 1982 and is still widely quoted to this day. Batchelor laid out his general philosophy in the Preface in the following terms:

> Finally, it may be worthwhile to say a word about the attitude that I have adopted to the problem of turbulent motion, since workers in the field range over the whole spectrum from the purest of pure mathematicians to the most cautious of experimenters. It is my belief that applied mathematics, or theoretical physics, is a science in its own right, and is neither a watered-down version of pure mathematics nor a prim form of physics. The problem of turbulence falls within the province of this subject, since it is capable of being formulated precisely. The manner of presentation of the material in this book has been chosen, not with an eye to the needs of mathematicians or physicists or any other class of people, but according to what is best suited, in my opinion, to the task of understanding the phenomenon. Where mathematical analysis contributes to that end, I have used it as fully as I have been able, and equally I have not hesitated to talk in descriptive physical terms where mathematics seems to hinder the understanding. Such a plan will not suit everybody's taste, but it is consistent with my view of the nature of the subject matter.

Batchelor consistently followed this philosophy throughout his research career, and equally in his teaching at both undergraduate and graduate level. It was a philosophy that did not endear him to 'the purest of pure mathematicians', for whom the idea that mathematics could 'hinder the understanding' was perhaps less than welcome; but it reflected the approach of his mentor G.I. Taylor, who had the genius of using just as much mathematics as is needed, and no more, in the analysis and elucidation of physical phenomena.

In 1950 Batchelor published an important paper (6) on the spontaneous growth of magnetic field (i.e. dynamo action) caused by turbulence in a highly conducting fluid. He recognized that, just as vortex lines tend to be stretched owing to the statistical lengthening of material lines in a turbulent flow, so the lines of force of a magnetic field, which are 'frozen' in the flow, will be similarly stretched with consequential intensification of the field, a process modified but not suppressed by weak diffusion effects. Batchelor argued, on the basis of Kolmogorov-type reasoning, that the magnetic energy would ultimately saturate, reaching equipartition with the energy of the small-scale dissipative ingredients of the flow field. The theory was controversial and was hotly debated throughout the 1950s. It is now known to be wrong, because it fails to account for the growth of a large-scale field associated with turbulent helicity; nevertheless, the arguments pioneered by Batchelor are still relevant to consideration of the small-scale fluctuations in magnetic field in the interstellar medium, and to saturation mechanisms when dynamo action occurs.

This work led to consideration of the effect of turbulence on 'material' lines and surfaces (9) and to more general questions relating to turbulent diffusion (4, 7, 8, 12). This sequence of papers culminated in two papers (the second in collaboration with Alan Townsend and Ian Howells) concerned with the small-scale variation of convected quantities such as temperature in turbulent flow (13, 14), which clarified the role of molecular diffusion processes (both thermal and viscous) in determining the tail of the temperature spectrum at large wavenumbers. In this definitive work, Batchelor succeeded in reconciling previous conflicting theories, and established a basis for all subsequent work on the 'passive scalar problem'.

For a more detailed and comprehensive account of Batchelor's contributions to the theory of turbulence, see Moffatt (2002).

During the 1950s, Batchelor attracted a number of talented people to form the core of a vigorous research group, including, for various periods, R.W. (Bob) Stewart (F.R.S. 1970), W. (Bill) Reid, Owen Phillips (F.R.S. 1968), Ian Proudman, Philip Saffman (F.R.S. 1988), Philip Drazin, Derek Moore (F.R.S. 1990), Stewart Turner (F.R.S. 1982) and Anthony Pearson. I was myself privileged to join this distinguished group in 1958. The research atmosphere at that time was vibrant. The discussions were extremely lively, particularly those at the Friday fluid mechanics seminars that Batchelor had initiated in 1947 and that over the years provided the vital meeting and sparring ground for the wider Cambridge fluid dynamics community. Batchelor himself would invariably pose incisive questions in discussions that would continue long after the end of the formal presentations. To present a seminar in this forum was both an honour and an ordeal! It was a fertile breeding ground for the development of a genuine spirit of enquiry and an ability to think creatively in free and open debate.

THE *JOURNAL OF FLUID MECHANICS*

Until 1956 there was no journal that was devoted to fluid dynamics in all its experimental and theoretical aspects, papers in fluid dynamics being widely spread over the literature of engineering, physics and mathematics. Batchelor perceived a need for a journal of a new kind, one that would include papers over the full range from those dealing with the most fundamental aspects of the subject right through to those dealing with applications in all sciences, whether geophysical, astrophysical, biological or technological, in which fluid dynamics plays a part. Together with George Carrier (Harvard), Wayland Griffith (Princeton University) and James (later Sir James) Lighthill, F.R.S. (then at Manchester University), as Associate Editors, and Brooke Benjamin (F.R.S. 1966) and Ian Proudman as Assistant Editors, he launched the *Journal of Fluid Mechanics*, the first issue of which appeared in May 1956.

One principle immediately distinguished this journal from others. This was that each Editor and Associate Editor should take personal responsibility for the handling of papers submitted to him, from the moment of submission, through the refereeing process, and right through to the final decisions on acceptance or rejection. The procedure ensured a very personal line of communication between each author and the journal, and an assurance that an unusual level of personal care and attention was indeed given to every paper submitted for consideration. Batchelor himself was scrupulous in the care that he gave to the refereeing process and in the interpretation, and often elucidation, of referees' reports in long correspondence that he would have with authors. It was his practice, in consideration of any potentially publishable paper, to offer copious advice on matters of presentation and to encourage resubmission for further consideration by referees, a process frequently iterated several times before final acceptance of a manuscript. Authors might have found this frustrating, even tedious, at the time, but Batchelor would invariably command respect in this protracted process, and gratitude when the final polished paper appeared in print.

The standard of the journal was high from the start, and it rapidly achieved international recognition as the leading journal of the subject. It was initially intended to publish one volume of six parts per year, but the influx of papers grew as the journal gained in prestige, and the number of volumes published annually grew proportionately. Batchelor retained firm control for four decades, although with a changing team of Co-editors and Associate Editors; only in 1999, by which time no fewer than 377 volumes of the journal had been published, did he, in failing health, finally relinquish the editorship to David Crighton, F.R.S., who had joined the team of Associate Editors in 1979. (Tragically, Crighton himself died just two weeks after Batchelor, on 12 April 2000; see Huppert & Peake (2001).) The *Journal of Fluid Mechanics*—or *JFM* as it is universally known—is still, under the current joint editorship of Steve Davis and Tim Pedley, F.R.S., outstandingly strong, and stands as a lasting memorial to the vision with which Batchelor initiated this ambitious project nearly half a century ago.

Batchelor's thoughts on the responsibilities and problems of journal editorship are contained in an article, 'Preoccupations of a Journal Editor' (22), that he wrote for inclusion in the 25th anniversary edition of the journal (see also Huppert (2000), which gives an illuminating interpretation of this side of Batchelor's work, and which also contains a nice selection of photographs from his life).

Head of Department, 1959–83

Before 1959, the Cambridge Faculty of Mathematics had no departmental structure and no accommodation other than the Lecture Rooms and Faculty Office assigned to it in the Arts School in Bene't Street. Lecturers in the faculty were college-based; research students would see their supervisors in college but would have little opportunity for communal interaction and exchange of ideas within a like-minded community. Batchelor was a leading spirit within the faculty to form the departments that would provide the natural setting for a more interactive research activity. DAMTP was established in 1959; Batchelor was appointed its first Head of Department, and simultaneously Reader (*ad hominem*) in Fluid Dynamics. The professors in the new department were Paul Dirac, F.R.S., and Fred (later Sir Fred) Hoyle, F.R.S., and the principal areas covered were high-energy physics, theoretical astronomy, and fluid and solid mechanics. Batchelor ruled the department from the outset on democratic principles; attendance at the termly staff meeting at which all issues were thoroughly debated was *de rigueur*.

The department was initially housed in scattered rooms on the site of the old Cavendish Laboratory; however, in 1963, Batchelor seized an opportunity presented by the move of Cambridge University Press to its new accommodation on Brooklands Avenue; this move vacated two large warehouse-style buildings in the area between Silver Street and Mill Lane. Batchelor immediately made the case for conversion of one of these buildings (the old machine shop of Cambridge University Press) for DAMTP. At the same time, Sir William Hodge, F.R.S., Head of the newly formed sister Department of Pure Mathematics and Mathematical Statistics (DPMMS) made a collusive bid for the second building. Both bids were granted by the university, and a conversion programme was rapidly agreed. Over the next few years, the departments were able to consolidate within these old Press site buildings, which provided an ideal, though latterly overcrowded, home for DAMTP and DPMMS for more than three decades.

Batchelor, however, faced a severe test of his authority at about this time. His appointment as Head of Department was for a five-year period, and in 1964 the Department had to consider the succession. It had originally been expected that the Headship would rotate at five-yearly intervals. However, it was clear that Batchelor wished to continue as Head, as certainly permitted by the regulations, and it was natural that he should do so in view of the impending move to Silver Street, which he had himself engineered and on which his future vision for the department was based. Hoyle, however, was unhappy about the way in which the department was being run, which he saw as unnecessarily bureaucratic, and he made a bid for the Headship. The various soundings that were made within the department led to a vote of confidence for Batchelor, who was in the event reappointed for a further five-year period. Hoyle broke relations with the department, and was later to become founding Director of the new Institute of Theoretical Astronomy (now the Institute of Astronomy) on Madingley Road.

After this stormy interlude, Batchelor's position was secure, and his authority was not challenged again. He was elected to the new Professorship of Applied Mathematics in December 1964, and his appointment as Head of Department was renewed on three subsequent occasions, in 1969, 1974 and 1979. On each occasion he offered to step down if the department so wished; but in fact he was temperamentally so well suited for the role, and so effective in it, that it was absolutely natural that he should continue. The department gained immeasurably in strength under his wise leadership, and it was a sad day when, in 1983, he relinquished the Headship on accepting 'early retirement'. As he would later say, he received an offer from the university that he could not refuse! Of course, early retirement in Batchelor's case meant simply a change of office within the department and a shift of emphasis in his work away from administration and towards the research and research-related activity that he loved. For a further 14 years he would regularly spend long working days at the department, when not attending conferences or lecturing abroad.

Although not an experimentalist himself, Batchelor had always recognized the need for close interaction between theory and experiment in fluid mechanics. With the move to the old Press site in 1964, he realized that the otherwise unusable basement area could accommodate a Fluid Dynamics Laboratory. This was an unusual, indeed revolutionary, suggestion, coming as it did from within the Faculty of Mathematics, and Batchelor had to overcome considerable opposition from the neighbouring powerful departments of Physics and Engineering before securing the funding that this required. The Fluid Dynamics Laboratory was nevertheless established, with Brooke Benjamin as its first Director, and very soon justified its existence through the use made of it by research students and others in the department, and the highly original style of experimentation that it encouraged. Similarly, Batchelor also successfully campaigned for the introduction of a practical course on Computer-Assisted Teaching of Applied Mathematics, a course that was to become a prototype for many such courses introduced in other universities in later years.

Batchelor's 24 years as Head of DAMTP saw a wonderful flowering of research activity and in particular within the fluid dynamics group, which expanded greatly during the 1960s and 1970s, embracing geophysical fluid dynamics with the appointments of Francis Bretherton, Adrian Gill (F.R.S. 1986) and Michael McIntyre (F.R.S. 1990), and biological fluid dynamics with the appointment of James Lighthill as Lucasian Professor in 1969 in succession to Paul Dirac. The number of research students steadily increased, as did the number of research grants administered by the department. There was a regular flow of Senior Visitors from all over the world, attracted by the reputation of the department, and themselves contributing to it. Batchelor worked ceaselessly for the good of the department within the various corridors of power in the university. He also fought vigorously to maintain the position and status of applied mathematics within the Mathematics Tripos and to maintain a strong flow of graduate students, via Part III of the Tripos and via scholarships from overseas, to the applied side. However, he continued to have little natural sympathy for pure mathematics, and relations with colleagues in DPMMS across the Faculty Board table were sometimes strained, to say the least.

Chairmanship of EUROMECH

As indicated above, Batchelor's international debut was in 1946 at the 6th International Congress of Applied Mechanics, in Paris. He was an enthusiastic adherent of the International Union of Theoretical and Applied Mechanics (IUTAM), founded in 1948, and became a familiar figure at the subsequent quadrennial congresses, which came under the IUTAM umbrella: London (1948), Istanbul (1952), Brussels (1956), Stresa (1960), Munich (1964), Stanford (1968) and Moscow (1972). For the last four of these he served on the Executive of the Congress Committee of IUTAM. This gave him an exceptionally broad view of international activity in both solid and fluid mechanics. During the early 1960s he recognized a need for greater scientific interaction specifically within Europe, and, together with Dietrich Küchemann, F.R.S. (of the Royal Aircraft Establishment, Farnborough), he set up a European Mechanics Committee whose function it was to stimulate such scientific interaction within the fields of solid and fluid mechanics—thus anticipating by some 20 years the various initiatives that would later emanate from the EC Directorates of Brussels! Batchelor was the Chairman of this 'EUROMECH' Committee from 1964 to 1987 (and was succeeded in this role also by David Crighton, under whose chairmanship the organization was reconstituted as the European Mechanics Society).

For the purpose of promoting interaction, the Committee established a series of Colloquia, themselves soon to be known as 'EUROMECHs'. The first of these, on the subject 'Boundary layers and jets along highly curved walls—Coanda effect', was held in Berlin in April 1965. By 1985 there were approximately 15 EUROMECHs each year; a total of 230 were held during Batchelor's chairmanship. His firm hand and meticulous attention to detail can be seen in the notes of guidance written for chairmen of Colloquia: three to five days' duration, participants from all countries of Europe 'extending eastwards as far as Poland and Rumania', organizing committee of six members for each Colloquium, not more than 50 participants, topics chosen to be of theoretical or practical interest but not devoted to details of engineering applications, introductory lectures to be included, presentation of current and possibly incomplete work to be encouraged, no obligation to publish Proceedings, and so on. These Colloquia were run on a financial shoestring, most participants finding their own individual sources of funding, but this seems to have had little adverse effect; on the contrary, the freedom from the constraints often imposed by grant-giving bodies gave EUROMECHs a freshness and spontaneity that was widely valued.

The inclusion of Poland was significant. Batchelor was, through IUTAM, a good friend of Wladek Fiszdon (Institute of Fundamental Technological Research, Warsaw), and had given him encouragement and help in the organization of the biennial Symposia on Fluid Mechanics in Poland that served so well to maintain communication between scientists from East and West during the long cold-war years. The link with Poland developed with the presence of Richard Herczynski, a younger colleague of Fiszdon, as a Senior Visitor in DAMTP in 1960/61. Batchelor attended the Fluid Dynamics Conference held in Zakopane, Poland, in 1963—one of the first at which any Western scientists were present—and had preliminary discussions then with Fiszdon and Herczynski about the need for greater European cooperation in science. He attended several of the subsequent biennial meetings and was involved much later, through Herczynski, in the traumatic events for Polish scientists during the solidarity years, always giving moral support when this was most needed.

Second wind in research, 1970–96

By 1960 it had become apparent to Batchelor that insurmountable mathematical difficulties lay ahead in dealing adequately with the central 'closure problem' of turbulence. As he was to say later (24) 'by 1960 … I was running short of ideas; the difficulty of making any firm deductions about turbulence was beginning to be frustrating, and I could not see any real break-through in the current publications'. These frustrations came to the surface at the now legendary meeting held in Marseille (1961) on the occasion of the opening of the former Institut de Mécanique Statistique de la Turbulence (Favre 1962). At this meeting, of which Batchelor was a key organizer, conventional ideas on turbulence were turned on their head. Kolmogorov himself revealed a flaw in his own theory, related to the intermittency of the process of viscous dissipation at the smallest scales of motion. This should have been no surprise to Batchelor because he, together with Townsend, had remarked on the phenomenon of the intermittency of the vorticity distribution in their 1949 paper 'The nature of turbulent motion at large wave-numbers' (5), but he found it hard to abandon the original Kolmogorov theory, a cornerstone of the dynamics of turbulence on which he had himself invested so much effort.

It was therefore perhaps no surprise that Batchelor should choose to focus, over the next few years, on his *Introduction to fluid dynamics* (15) and on the editing of the fourth and final volume of *The scientific papers of Sir Geoffrey Ingram Taylor* (the previous three volumes having been published under his editorship in 1958, 1960 and 1963). In the course of all this work he was drawn towards the low-Reynolds-number problems that arise in the 'microhydrodynamics' of suspensions of small particles or bubbles or droplets in fluids, a subject that was now to give him a new lease of research life.

The rheology of fluid suspensions was a long-standing problem, first tackled by Einstein in 1906. Batchelor was puzzled by the fact that Einstein had arrived at his conclusions concerning the effective viscosity of a suspension through the manipulation of divergent integrals, a procedure that on the face of it was unjustifiable, although the conclusions seemed quite plausible. It is of course perhaps a measure of genius when correct results are found by methods that are at first sight inadmissible, only to be placed on a rational basis some decades later! However that may be, it was this problem that led Batchelor to develop a systematic procedure for handling these divergences, a procedure that is set out in his seminal paper 'Sedimentation in a dilute dispersion of spheres', published in *JFM* in 1972 (19). It is significant that this paper was twice cited as a 'landmark paper' of the twentieth century, in a booklet *Landmarks in mechanics* published by IUTAM to mark Millennium Year 2000. One of the citations was from Professor A. Acrivos, Einstein Professor at City College of the City University of New York, who wrote as follows:

> In this paper, Batchelor presented an ingenious and general technique for renormalizing the divergent integrals by taking advantage of the bulk constraints which are imposed in the formulation of any transport problem. This technique is much more than a mathematical trick in that it requires deep physical insight as well as a detailed appreciation of the physical problem being addressed, and varies from one problem to another. In applying Batchelor's method, it has become possible therefore to solve in a rigorous fashion a large number of classical problems, of which the extension to higher order in the particle concentration of Einstein's well-known expression for the viscosity of a suspension of solid spheres is but one example.

I am indebted to Professor Acrivos, who has written further as follows concerning Batchelor's work of this period:

> A related fundamental problem involves the determination of the bulk stress in a flowing suspension. Here, Batchelor [(16)] developed an exact formalism for determining this quantitatively and, by making use of a slender-body theory for Stokes flows which he constructed [(17)], derived a widely quoted expression for the elongational viscosity of a suspension containing a dilute (by volume) dispersion of aligned slender rods [(18)]. This experimentally verified expression, which has shed considerable light on the phenomenon of drag reduction, predicts that even when the suspension is dilute (by volume) its effective elongational viscosity can be orders of magnitude greater than that of the ambient liquid if the aligned rods are sufficiently long and slender.
>
> Batchelor's contributions to microhydrodynamics were not limited, however, to his own published papers, for he acted as a mentor and advisor to a host of other researchers as the following example from my own experience will illustrate. In 1982, in one of my periodic visits to Cambridge, I discussed with him an experimental observation by one of my students which had me completely mystified. This pertained to the fact that, under the action of shear, an initially settled bed of heavy non-colloidal particles, in contact with a lighter fluid above it, resuspends and the heavy particles remain in suspension even in the absence of inertia and Brownian forces. This obviously required the existence of a lift force under creeping flow conditions, which would counteract the force of gravity, but neither I nor my students could think of a mechanism which might be able to generate such a lift. A few weeks later, I received a letter from Professor Batchelor pointing out to me that the particles in a concentrated suspension under shear execute irregular motions and that this shear-generated random motion is akin to diffusion and can therefore create a flux of particles from regions of high particle concentration to low, thereby counteracting the flux due to gravity. This observation led me then to study in depth

> the mechanism of shear-induced particle diffusion which not only explains the viscous resuspension phenomenon referred to above, but has also been shown to play a major role in governing the flow properties of a large class of concentrated suspensions.

Batchelor's breakthrough (19) in microhydrodynamics in 1972 laid the basis for much of his subsequent work, as for that of the new team of research students, notably John Hinch (F.R.S. 1997) and John Rallison, who were attracted to work within his group. His publications in microhydrodynamics continued until 1996 when, with J.M. Nitsche, he published his final technical paper 'Break-up of a falling drop containing dispersed particles' (26).

Batchelor also returned twice to turbulence during this second phase of his research career, on each occasion with a highly original contribution. The first of these was his 1980 paper 'Mass transfer from small particles suspended in turbulent fluid' (21). Here, 'small' means small in comparison with the inner Kolmogorov scale, so that he was able to represent the 'far field' as a uniform gradient velocity field (an approximation that he had previously exploited in the problem of turbulent diffusion (13)). Batchelor assumed that the Péclet number was large, and he solved the advection–diffusion equation in the 'concentration boundary layer' around the particle, to calculate the net rate of mass transfer from the particle. His final return to turbulence (in collaboration with V.M. Canuto and J.R. Chasnov) came with his 1992 paper 'Homogeneous buoyancy-generated turbulence' (23). Here he considered a field of turbulence generated from rest by an initially prescribed random density distribution giving a random buoyancy force. The driven turbulence of course immediately modifies the distribution of buoyancy forces, and an interesting nonlinear interaction between velocity field and buoyancy field develops. As the authors state in their abstract, 'the analytical and numerical results together give a comprehensive description of the birth, life and lingering death of buoyancy-generated turbulence'.

THE FINAL YEARS

Batchelor had suffered a cycling accident in Cambridge in 1973 which affected his balance and left him deaf in one ear. He found this frustrating, but nevertheless coped well with the difficulties. More serious was the onset of Parkinson's disease around 1996, which he found increasingly debilitating. The loss of Wilma, who died suddenly in November 1997, was a severe blow, and George found it very hard to adjust to the situation in which he found himself. He moved from Cobbers to rooms in Trinity College in 1998, and still managed for some time to walk to his beloved DAMTP in Silver Street; but the progress of Parkinson's disease was remorseless and he died just three weeks after his 80th birthday, after a brief spell in a nursing home near Cambridge.

It had been his stated intention to write a sequel to his 1967 textbook treating the great range of applications of fluid dynamics to fields in which he had been personally involved. By 1996 he realized that this task was beyond him but he initiated instead a volume, *Perspectives in fluid dynamics*, consisting of 11 chapters by different authors covering some of these fields. Grae Worster and I were drawn into this project, but the concept and the motive force came from George. The volume was published some months after his death (28).

As I write, I sit in the office in DAMTP that George occupied, surrounded by his books and papers and an amazing accumulated correspondence from half a century in science—a detailed and well-ordered archive from a period that has seen great developments in fluid dynamics as a flourishing branch of science in which Batchelor himself played an absolutely central role. His legacy to science is fourfold: through his personal research achievements and his famous textbook; his founding of EUROMECH and promotion of East–West collaboration in Europe; his pioneering role as founding Head of DAMTP, Cambridge; and above all, his founding Editorship and loving stewardship of the *Journal of Fluid Mechanics*.

Batchelor was ascetic by instinct, frugal without meanness, with a dry humour, and perhaps giving an impression of austerity in later years, although always in practice approachable and a source of sound advice to colleagues and research students alike. He will be remembered as a man of great scientific integrity, penetrating judgement and deeply held convictions. On these I can perhaps do no better than quote his own words concerning the pursuit of natural knowledge as 'a civilising and ennobling activity' on which he wrote in the following terms (27):

> Through having common objectives and principles by which new knowledge is assessed and disseminated, scientists concerned with a particular field like fluid mechanics form an international community of great unity and moral strength. I believe that the understanding, trust, and goodwill between members of this scientific community transcends geographical and political boundaries and constitutes one of the most important forces for international harmony and friendship in the world today.

George Batchelor led his life in this very positive conviction to which his great achievements bear ample testimony.

Awards

1951 Adams Prize, University of Cambridge
1957 Fellow of The Royal Society
1959 Foreign Honorary Member, American Academy of Arts and Sciences
1972 Ordinary Member, Royal Society of Uppsala
1975 Foreign Member, Polish Academy of Sciences
1984 Associé Etranger, Académie des Sciences, Institut de France
1986 Agostinelli Prize, Accademia Nazionale dei Lincei
1988 Timoshenko Medal, American Society of Mechanical Engineers
1988 Royal Medal, The Royal Society
1989 Corresponding Member, Australian Academy of Sciences
1990 Emeritus Member, Academia Europaea
1994 Foreign Associate, US National Academy of Sciences
1997 G.I. Taylor Medal, US Society of Engineering Science

Honorary doctorates

1959 University of Grenoble
1974 Technical University of Denmark
1986 McGill University, Montreal
1989 University of Michigan
1994 University of Melbourne
1995 Royal Institute of Technology, Stockholm

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My main source for the details of George Batchelor's early life is his own unpublished paper, 'Autobiographical notes on an academic life', written during his last years. I acknowledge also the most helpful comments on a first draft of the memoir from his daughters Adrienne Rosen and Bryony Allen, and from current and former colleagues at DAMTP, Cambridge.

The frontispiece photograph was taken in 1959 by Walter Bird, and is reproduced with permission from Godfrey Argent.

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(4) (19) Diffusion in a field of homogeneous turbulence. I. Eulerian analysis. *Aust. J. Sci. Res.* A **2**, 437–450.

(5) (21) (With A.A. Townsend) The nature of turbulent motion at large wave-numbers. *Proc. R. Soc. Lond*. A **199**, 238–255.

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(22) (77) 1981 Preoccupations of a Journal Editor. *J. Fluid Mech*. **106**, 1–25.

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