SIR WILLIAM IAN AXFORD

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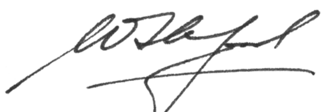

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Elected FRS 1986

By William Allan

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William Ian Axford was born and educated in New Zealand, receiving his ME and MSc degrees from Canterbury College of the University of New Zealand in 1956. He completed his PhD at Manchester University in 1960 and spent the following year at Cambridge University before moving to the Defence Research Board of Canada. From 1963 to 1974 he held professorships at Cornell University and the University of California at San Diego. From 1974 to 2001 he directed the Max Planck Institute for Aeronomy in Germany, with two three-year periods of leave in New Zealand in 1982–85 and 1992–95. Ian Axford was one of the greatest plasma physicists of the space age. He made fundamental contributions to a wide range of topics in the fields of space physics and astrophysics, including the dynamics of the Earth's magnetosphere, the magnetic field reconnection process, the Sun's atmosphere and the formation and evolution of the solar wind, the interaction of the solar wind with the interstellar medium and with comets, cosmic ray propagation and modulation in the Solar System, the acceleration of cosmic rays in supernova shocks, and the use of robotic spacecraft in the exploration of the Solar System. Ian was also a remarkable science administrator, completely restructuring the Max Planck Institute for Aeronomy and transforming it into one of the world's leading space and atmospheric research institutes. He was a great advocate of international collaboration in science, and reinvigorated several flagging institutions such as the European Geophysical Society and the International Council of Scientific Unions Committee on Space Research.

Family background

William Ian Axford (Ian) was born on 2 January 1933 at the small country town of Dannevirke in southern Hawke's Bay, New Zealand. His mother, May Victoria Thoresen, was the youngest of 10 children born to Olaf Thoresen and Petrea Pedersen, children of emigrants from Norway brought to New Zealand in the 1870s to fell the bush and build railways. It was in Dannevirke

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that May met Ian's father, John Edgar (Jack) Axford, who had left Scotland for New Zealand in 1928 to begin a new life. Jack had completed an apprenticeship as a patternmaker at the Glasgow engineering firm of J. J. Weir & Co., but the depressed state of the shipping industry at the time meant that he was unable to find employment. When an injury put paid to an alternative career in professional football he made the decision to emigrate. In 1936 the Axford family, which now also included Jack's parents, moved up the coast to Napier, the port and coastal town of Hawke's Bay. A sister to Ian, Janet Ann, was born in 1940.

Early life and education

Napier was recovering from a massive earthquake that in 1931 had reduced its business district to rubble and caused death and destruction in the wider area. Rebuilding of the town and port facilities began almost immediately, meaning that Napier was largely untouched by the looming depression. The shining new Napier was the place to live and work, and Jack soon found employment with J. J. Niven Engineering Ltd. In his spare time he founded the Napier Rovers soccer club, becoming chairman and coach. When he died in 1958 at the early age of 50 years, he was Niven's foreman patternmaker and Napier City Rovers was one of the top provincial teams in the country.

Ian attended primary and secondary schools in Napier. His school reports show consistently good results. He was dux of Napier Boys' High School and was awarded a special bursary in engineering. In 1951 he commenced his studies at the Canterbury College of the University of New Zealand (now the University of Canterbury).

He commented later that he was grateful for aspects of his early education even though in that postwar period there were shortages of everything—teachers, equipment and facilities. 'It [education] was free and New Zealand being a classless society meant that anyone who wanted could go to university. If you were good at something you could study it, no matter what your background or how much money you had' (Ingrid Horrocks, NZEdge interview, 14 December 2006).

On completion of his undergraduate studies, Ian was awarded the first Todd Motors research scholarship and in 1956 graduated Master of Engineering with Distinction and Master of Science (first class) in mathematics.

During his student years in Christchurch, Ian always returned to Napier for the long summer vacation and the cricket season. In January 1955 he married born and bred Napier girl Joy Lowry, a trained teacher who was a music specialist at the local intermediate school. Returning with Ian to Christchurch, Joy continued to teach and was able to attend university part time. (A Bachelor of Arts degree, majoring in music, was completed 37 years later at Victoria University of Wellington.)

In 1957 he was appointed to the New Zealand Defence Scientific Corps as a Flight Lieutenant in the Royal New Zealand Air Force (RNZAF). This enabled Ian, who by now had a wife (Joy) and two small children, to undertake postgraduate study in aerodynamics at Manchester University in England. The RNZAF no doubt saw Ian, with his aptitude and qualifications in mathematics and mechanical engineering, in a range of design roles. But 1957 was the year of the first Sputnik and the start of the late astronomer Patrick Moore's BBC television show *The Sky at Night*. Ian was an avid viewer, and his growing interest in astronomy was to redirect his career path. He rapidly completed his PhD in applied mathematics in 1959 with a thesis entitled 'Ionisation fronts in interstellar gas and some other problems of fluid dynamics'. On completion of his thesis, he spent a year at Cambridge University solving magnetohydrodynamics (MHD) problems.

Almost everyone who grows up in New Zealand plays some sort of sport, and Ian was no exception. An enthusiastic cricketer, he represented his high school, university and province in this sport, mentored by his grandfather William (Bill) Axford, a highly respected Napier umpire. During his time in Manchester, Ian played for Werneth in the Central Lancashire League. Captain of the university cricket team, in 1959 he was elected to the XXI Club, established in 1932 to promote sporting excellence. At Cambridge he gained selection to the university team and achieved his dream of playing at Fenner's (Cambridge University's cricket ground), but his aspirations were short lived, playing in two fixtures only. When time allowed, Ian played for the London–New Zealand Club team.

In North America

After his year in Cambridge, Ian was seconded by the RNZAF to the Defence Research Board of Canada. He was one of four members of the Theoretical Studies Group at the Defence Research Telecommunications Establishment in Ottawa, spending 1960–62 there. Ian's work in this group led to an interest in the magnetosphere and resulted in his best-known paper (see the section Scientific Research for more detail). In the hot Canadian summers, Ian enjoyed the cricket matches on the Governor General's grounds in Rockliffe Park and won the batting trophy in 1961.

After completing his contract with the RNZAF at Shelly Bay, Wellington, New Zealand, the family was on the move again. In mid 1963 Ian accepted the position of associate professor in the Astronomy Department of Cornell University, New York; he was appointed full professor in 1966. He was attracted to Cornell because of the interest in the Moon stimulated by department head Tommy Gold (FRS 1964). During his time at Cornell, Ian wrote and published prolifically on a variety of topics including cosmic rays, synchrotron radiation, stellar winds, ionization fronts and plasma waves, working particularly with L. J. Gleeson, M. Simon, R. C. Newman and F. Einaudi, among others.

In 1967 Ian was appointed to a joint position as professor in the Departments of Physics and APIS (Applied Physics and Information Science) at the newly established University of California in San Diego. His published output became even more prolific and wide-ranging. It included work on solar modulation of galactic cosmic rays, interaction between interstellar helium and the solar wind, the polar wind, magnetospheric convection, reconnection of magnetic field lines, thermal protons in the ionosphere and magnetosphere, the Compton–Getting effect, solar wind ion composition, galactic winds, neutral hydrogen in cometary comas, and cosmic ray gradients determined from Pioneer 10 and Pioneer 11. His co-authors included L. A. Fisk, W. Fillius, L. J. Gleeson, W.-H. Ip, T. E. Holzer, T. Yeh, P. M. Banks, A. F. Nagy, D. A. Mendis and H. E. Johnson.

In the early 1960s the American Geophysical Union acknowledged that space science was becoming a major research area, and created a separate *Space Physics* section of its *Journal of Geophysical Research* (*JGR–SP*). In the next few years, publication rates in *JGR–SP* increased greatly year by year. Ian took over the editorship of *JGR–SP* for 1969–73 and commented, 'I was convinced … that it was important to be seen as being, and also to be, strictly neutral'

(38)*. *JGR–SP* was thriving, but it did not quite have the reputation for quality that it now has. Ian said, 'The aim of a journal after all is to publish papers, not reject them, so I put on a fierce expression, gave nobody favoured treatment, and made sure that all papers were properly refereed' (38). He tells a tale of missing a deadline through travel, resulting in a thin journal issue. This was taken as indicating how tough the editorial and refereeing policies were, although Ian said that papers were accepted if two referees approved, even if this required asking five or six referees to comment. Ian was impressed by the dedication of referees, and brought in a policy of acknowledging referees by name with their consent, thus making it clear that papers were being handled according to a standard procedure and providing a check on the Editor's choice of referees.

The demands of the Editor's job left Ian feeling burned out even before the end of his term, but he left behind him a journal of exceptional quality. His research output and the success of *JGR–SP* greatly enhanced Ian's international reputation, leading to an invitation to participate in a German committee that was soon to redefine his career and have a major impact on international space science.

Max Planck Institute for Aeronomy, 1974–2001†

In January 1958 two institutes of the German Max Planck Society, the Institute for Ionospheric Research and the Institute for Physics of the Stratosphere, had been merged to form the Max Planck Institute for Aeronomy (commonly known as MPAe), although the two sub-institutes remained under separate scientific leadership. (Aeronomy is a term coined by Sydney Chapman in 1946 to describe the science of the upper region of the Earth's atmosphere where dissociation and ionization are important.)

Although much good work was carried out between 1958 and 1974, MPAe had never achieved a global presence because aeronomy came to be regarded as somewhat 'old-fashioned', and also because the Institute was situated in the rural village of Katlenburg-Lindau near the Harz Mountains in central Germany, close to the border between East and West Germany. This region was seldom visited by internationally known space scientists. With pending retirements of two MPAe directors in 1975 and 1977, the Max Planck Society in 1974 appointed a 'Closing-down Committee' that included Ian Axford as a member. After careful deliberation, including consideration of the long-term commitments of MPAe to several current or new European space projects, the potential of MPAe staff to contribute to these, and the growing importance of space science in a global context, the committee concluded that at least the space science part of MPAe should be kept alive. It seems very likely that Ian's advocacy was a major influence on this decision. Indeed, the committee soon proposed that Ian should be invited to become MPAe's space science director, and the Max Planck Society accepted this. Ian became a Scientific Member of the Max Planck Society, one of the first foreigners to be elected to this position.

The move of Ian's household from the sandy beaches of Southern California to a small remote village in rural West Germany was more than a minor disruption for the family of six. It took place in the summer of 1974. The elder son and daughter, who were about to embark on their university studies, returned to New Zealand and enrolled at Canterbury University and

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

† Much of this section is based on presentations by A. K. Richter (Richter 2010).

Massey University, respectively. The younger son and daughter (with puppy) went with Ian and Joy to Germany, and both attended local schools for the next eight years.

Ian found that his first job at MPAe was to dispose of 52 plan (permanent) positions, no easy matter given the employment laws in Germany. Ian said 'this was achieved with no great strife'. One can infer that the lack of strife says volumes about Ian's personality and management skills rather than that the job was actually straightforward. The result was a tight organization with 200 plan positions and more than 50 others (PhD students, guest scientists and time-limited positions).

Although Ian's remit was to focus on space science rather than ionospheric and upper atmospheric research, he found himself much taken with the technology and future possibilities of the latter research at MPAe. He supported various existing projects such as the Ionospheric Heating Facility at Tromsø, and initiated new projects such as the Scandinavian Twin Auroral Radar Experiment (STARE). On the basis of this support, the Max Planck Society also accepted Ian as director for these research areas, and thus Managing Director for the whole of MPAe.

As Managing Director, Ian completely reorganized the structure of MPAe by doing the following:

(i) combining all activities in one building;
(ii) introducing one service section for all scientists, including design, construction, workshops, laboratories, test and calibration facilities and computing, with the 'Technical Meeting' chaired by the 'technical director' for the organization of all services;
(iii) upgrading all design and technical departments in both hardware and software to the highest world-class standards, to be able to build and test all hardware and software in house;
(iv) arranging for the best possible working conditions for all scientists and engineers at MPAe, whether in house or guests from abroad, and the greatest possible freedom in research and cooperation with other institutes and/or projects, under the 'creative-common-attribution licence' (the Axford principle);
(v) introducing new ways of cooperation and co-management and new openness in information and communication;
(vi) extending areas of research considerably in both experiment and theory (open research and open resources);
(vii) initiating an extended guest scientist programme (20–30 a year) and cooperation worldwide, filling new permanent positions only rarely for new fields of research; and
(viii) having MPAe scientists serve in many national and international positions, boards and committees.

This complete reworking led to MPAe Lindau finally becoming known worldwide as 'the Axford place' (figure 1).

Ian mobilized the directors, scientists and engineers by introducing bottom-up co-management on equal terms; by encouraging travel to meetings and conferences, and visits to other institutes and colleagues abroad, with corresponding return visits expected; by allowing all staff (permanent or temporary) to participate in any project, mission, experiment, study team or publication that they felt able to contribute to; and by expecting doors to stay open and everyone to be approachable and responsive. Ian's slogan was 'let everyone do what he wants to do, because when he wins we all win, but when he loses only he loses; but no-one will

Figure 1. Ian at the MPAe sign in Katlenburg-Lindau. (Photograph by courtesy of Joy Axford; photographer and date unknown, probably the late 1990s.) (Online version in colour.)

ever walk alone!' (Richter 2010). The MPAe culture was extremely unusual in its equality and openness, and much of its ensuing success can be attributed to that culture.

Ian's guest programme involved inviting experts for teaching, smart young scientists for cooperation, and 'third-world' scientists to help develop their work, to learn and to carry the science message back to their home countries. It also included involving local scientists in modern experiments and theories, and increasing the number of accepted publications. At a more informal level, a friendly environment was created by turning the Institute's old buildings into guest houses; appointing permanent contact secretaries; involving local kindergartens and schools; providing guest cars; arranging German courses, pot-luck parties and celebrating Fasching (the carnival season); expecting permanent staff to 'adopt' visitors; and above all by Joy and Ian Axford serving as warm and generous hosts. Personally, I can vouch for the effectiveness of the guest scientist programme: my year at Lindau in 1981–82 and subsequent collaborations working with STARE led to an enormous development of my career in magnetospheric physics and to the formation of permanent friendships.

The transformation of MPAe was supported by the other members of the MPAe directorial group (G. Pfotzer until 1977, V. M. Vasyliunas, H. Rosenbauer and T. Hagfors). It led to the Institute's increasingly high profile in the world of space and upper atmospheric science, particularly through contributions at a very high level to instrumentation, data acquisition and analysis on many and varied international space missions as well as ground-based ionospheric and atmospheric systems.

Ian and Tor Hagfors were due to retire in 1998. With this in mind, the MPAe directorial group planned a shift in emphasis away from the remaining ground-based research towards a dominance of Solar System research, including the proposed appointment of a new director in the field of planetary science. However, all members of MPAe were shocked to learn in October 1996 that the Max Planck Society again intended to close the Institute. The reasons

Figure 2. Ian and Tor Hagfors (left) with a street display during the 1996 campaign against the closure of MPAe. (Photograph by courtesy of Dr Patrick W. Daly of the MPS.) (Online version in colour.)

given were political and financial rather than scientific, namely that resources were required for the establishment of new institutes in the eastern part of the recently reunified Germany.

A campaign was quickly organized to save MPAe (figure 2). Political lobbying of regional and national politicians was initiated. Ian contacted all former and current MPAe visiting scientists and collaborators, asking them to write letters to the president of the Max Planck Society to express their feelings about MPAe and the proposed closure, with copies to be forwarded by Ian to the appropriate politicians.

Even Ian himself was probably surprised by the outpouring of support from hundreds of individuals and organizations around the world. Virtually all expressed astonishment and shock that the Max Planck Society could even contemplate closing an institute of the international stature enjoyed by MPAe. Most expressed the opinion that closure would be extremely damaging to European space science in particular, and to the many international space projects involving major MPAe contributions. Many also expressed the opinion that closure would be very damaging to Germany's reputation as a world science and technology leader.

It seems that the Max Planck Society leadership had not realized the importance of MPAe to the world space science community. They quickly revised the closure plan and consulted the MPAe directors on the Institute's future. The Max Planck Society Senate decision in 1997 was very similar to the internal plan developed earlier, namely that emphasis would shift to Solar System research while ground-based research would be wound down as older staff retired. MPAe would remain in the village of Katlenburg-Lindau. Finally, after the retirement of Helmut Rosenbauer in 2004, MPAe was renamed the 'Max-Planck-Institut für Sonnensystemforschung (MPS)', or the Max Planck Institute for Solar System Research.

Ian never accepted the usefulness of 'manned' spaceflight as a scientific endeavour (rather than as a political exercise). He felt strongly that robotic spacecraft would give an enormously greater scientific return at a vastly lower cost, particularly for deep space missions to the outer planets and beyond. Under his influence, the list of robotic space missions involving MPAe/MPS became long, including GEOS, Helios, Ulysses, Galileo, SOHO, Messenger, Cluster, Giotto, Interball, Geotail, Cassini-Huygens, Equator-S, STEREO, BepiColombo, Rosetta, Exomars, Mars Express, Venus Express, Chandrayaan, Phoenix, Herschel, SMART-1, SOFIA, Dawn, and Solar Orbiter. Perhaps Giotto was the most spectacular in the early days, with the MPAe close-encounter camera providing the first images of Comet Halley's nucleus. Ian's legacy therefore includes a significant part of our current knowledge of the solar atmosphere and the solar wind, comets, planets and planetary magnetospheres.

Scientific research

Ian's scientific work was based in the area of fluid dynamics and MHD, the study of conducting fluids threaded by magnetic fields. He applied and extended MHD in a continually expanding region of the Universe: from the Earth's atmosphere and magnetosphere to the magnetospheres of other planets in the Solar System, to comets and the solar wind, to cosmic rays in the inner Solar System, to the effect of the outer heliosphere (the Sun's extended atmosphere) on cosmic rays, to cosmic ray acceleration processes in supernova shock waves, and to cosmic ray processes in galaxies and galaxy clusters.

Ian worked in many places and on many topics during his career. In the following sections I describe Ian's scientific work with emphasis on topic rather than place. My impression is that Ian's method of moving to a new topic was to read a range of review papers on that topic, identify the gaps in the science, and develop ideas that might fill in the gaps. He then looked for bright young scientists and encouraged them to work on his ideas, helping them through difficult patches and suggesting general approaches, leaving them to work at a greater level of detail. Many of Ian's important papers are of the form 'XXX and Axford, 19xx', showing the effectiveness of this method for the young scientists concerned. The 'XXX' usually became well-regarded senior scientists in their own right.

Of Ian's many contributions to the study of astrophysics and Solar System research, the following are highlights selected to give a flavour of the scope and diversity of Ian's scientific work.

Beginnings: mainly fluid dynamics, MHD and ionization

Ian's earliest work involved boundary layer problems in fluid dynamics, a topic related to his appointment to the RNZAF. In late 1956 Flight Lieutenant Axford gained a Defence Scientific Corps posting, leading after Air Force training to his enrolment at Manchester University to study fluid dynamics in the group under James (later Sir James) Lighthill FRS. An article in a Wellington newspaper at the time said, 'His future work will be concentrated on aerodynamics, including basic research on aircraft design.' This did not quite come to pass.

Lighthill's group at Manchester was interested in the relatively new field of MHD, and Ian took up this challenge with enthusiasm. Under the supervision of Allin Goldsworthy he completed his PhD thesis in two years, publishing three papers in the following year (1960), on boundary layers, the oscillating plate problem in MHD, and the stability of plane current–vortex sheets. His fourth thesis paper, in 1961, was a major work on ionization fronts in interstellar gas (1), presaging his future consuming interests in space physics and astrophysics. This paper considered the effects of ionizing radiation from a young hot star on the surrounding interstellar gas. It presented a comprehensive analysis of the structures of all types of ionization front and how they depend on the density of the interstellar gas and the spectral type of the star's radiation, concluding that the most important condition for waves of this type to occur is that strong cooling effects should be present.

Having completed his thesis work with a year to spare (including 'methodically inserting magnetic fields into all the standard problems of fluid dynamics and eventually becoming reasonably proficient in dealing with them' (38)), Ian moved to Cambridge University and worked in the group under George Batchelor FRS. He spent a very enjoyable year encountering a variety of interesting people involved in geophysics and astrophysics, and absorbed a great deal of somewhat random information in these fields. 'This rather haphazard entry into space physics and astrophysics, for neither of which I had ever trained, was in many respects ideal, as I had no preconceptions and found everything incredibly interesting' (38).

Into space: the Earth's magnetosphere

After Cambridge, Ian was seconded to the Defence Research Board of Canada. He found himself at the Defence Research Telecommunications Establishment in Ottawa, as part of the 'Theoretical Studies Group' recently set up by Colin Hines and including George Reid and Jules Fejer. At first, Ian was not very enthusiastic about this move, but he soon realized that it was ideal for him because the field of space science was just taking off.

After preliminary work with Hines and David Whitehead on the link between gravity waves, wind shear and sporadic ionization density enhancements below the ionospheric E-region (leading to a significant paper (4)), Ian began to investigate the magnetosphere. This term had been introduced by Gold (1959), defined as the region where the geomagnetic field has an important if not dominant role in determining the behaviour of plasma, and is a concept (based on MHD) emphasizing the wholeness of magnetic field lines. Ian insisted that, on this basis, the ionosphere is part of the magnetosphere, and therefore 'the magnetosphere begins at about 100 km altitude and ends at the magnetopause where the solar wind takes over' (38). The magnetopause is the boundary between the geomagnetic field and the magnetic field of the solar wind.

Ian's key work in the magnetosphere was a paper with Hines entitled 'A unifying theory of high-latitude geophysical phenomena and geomagnetic storms' (2) (figure 3). This became Ian's most-cited paper, with 924 citations to date in the scientific literature, although Ian quipped that the work is 'often cited and sometimes sighted but rarely read' (38). The basic premise was that a 'viscous-like' interaction occurs between material in the outer part of the magnetosphere and the Sun's outward-flowing atmosphere (known as the solar wind) beyond. As shown in figure 4, the solar wind flow impresses a motion in the magnetosphere in which

Figure 3. Ian and Colin Hines (right) discussing magnetospheric convection in 1961. (Photograph by courtesy of the Communications Research Centre Canada.)

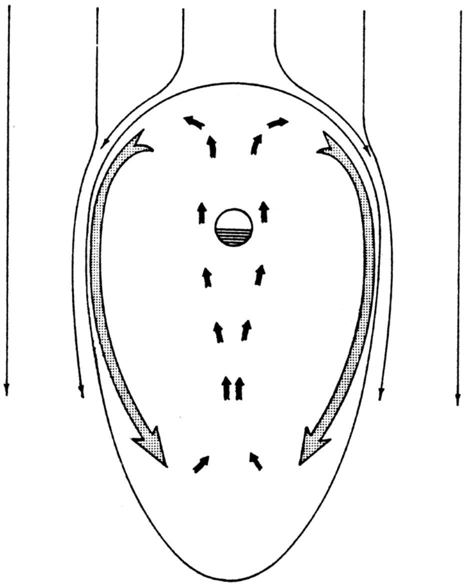

Figure 4. The motion impressed on the magnetosphere by a viscous-like interaction with the solar wind (equatorial section with solar wind blowing from top to bottom). The viscous-like interaction causes tubes of force that lie near the surface of the magnetosphere to be pulled around into the geomagnetic tail (large arrows). A return flow (small arrows) takes place in the interior of the magnetosphere. (Reprinted, with permission, from (2). Copyright © Canadian Science Publishing or its licensors.)

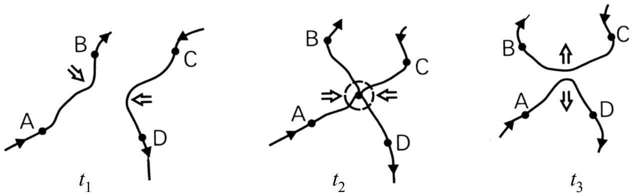

Figure 5. Reconnection: A, B and C, D are connected at t_1. The connection is broken at t_2. B, C and A, D are connected at t_3. (Reprinted from (45). Copyright © 2002 Elsevier; reproduced with permission.)

tubes of magnetic force are pulled around into the geomagnetic tail (large arrows). A compensating return flow towards the Sun must then occur in the interior of the magnetosphere (small arrows). Axford and Hines showed that this process of 'magnetospheric convection' could explain many diverse phenomena observed in the ionosphere and magnetosphere. Indeed, 'that plasma could simply be made to flow deep into the magnetosphere, be energized in the process, and show up partly as the nightside aurora, was a complete break from current thinking' (38).

Figure 4 essentially shows a closed magnetosphere in which magnetic flux tubes circulate entirely within the magnetopause. This is a consequence of the assumed viscous drag mechanism, the details of which were unspecified by Axford and Hines. Some type of continued stress in the outer magnetosphere is required to counter the resistance of the ionosphere to motions occurring in the magnetosphere. Ian soon accepted that viscous stress alone produced a type of convection that was inconsistent with some observations. He came to favour an alternative driver for the convection process that was proposed at about the same time by Dungey (1961). This was known as 'reconnection', a mechanism that has been invoked in several areas of Solar System physics. However, Ian noted subsequently that 'it is a rather subtle process and there have been at times misunderstandings which have actually slowed progress, especially in magnetospheric physics' (46).

The reconnection process is shown in simplified form in figure 5. The points A, B and C, D are connected on separate magnetic flux tubes at time t_1 in an ideal perfectly conducting plasma. The flux tubes are forced together by plasma flows and the connection is broken at t_2. Points B, C and A, D are now connected and the 'reconnected' flux tubes are pulled apart at t_3. The subtleties arise in the small reconnection region within the dashed circle at t_2, where non-ideal effects such as finite conductivity enable the actual reconnection to occur. The arguments about the details of this process are many and varied, but it is now widely accepted that reconnection provides the driving stress for magnetospheric convection. In essence, magnetic flux tubes in the solar wind are forced against the magnetosphere on the dayside and, under certain conditions, reconnect with magnetospheric flux tubes. The solar wind carries these reconnected flux tubes towards the geomagnetic tail (or 'magnetotail') on the nightside of the magnetosphere, providing the stress required to drive internal convection. As opposed to the earlier picture of a closed magnetosphere, the new picture is that of an open magnetosphere in which plasma can both enter the magnetosphere from the solar wind and leave the magnetosphere into the solar wind.

Ian contributed many ideas on the properties of the open magnetosphere (see, for example, (3, 6, 9, 16, 40)). He also studied the properties of the reconnection process itself (see, for example, (18, 28, 46)) and proposed what has been called 'the Axford conjecture' (28), that although reconnection can only occur if there is a non-zero electrical resistivity (or some other departure from ideal MHD), the process is primarily governed by large-scale dynamics and boundary conditions, not by the value of the resistivity. Ian's legacy to magnetospheric physics is immense and will continue to guide researchers for years to come.

Cosmic rays and astrophysical plasmas

Ian first became interested in cosmic rays just before leaving Canada in 1962. After six months in New Zealand he accepted a position at Cornell University and in 1967 moved to the University of California at San Diego. He was caught up in the excitement of the 'space age' during the 1960s, but among many other projects he began working seriously on cosmic rays. It could be said that this became a passion of his, as he contributed to the field throughout his scientific career; some 20% of his many publications relate to cosmic rays.

Cosmic rays in the heliosphere

Galactic cosmic rays (GCR) arrive in the vicinity of the Solar System from regions of the Galaxy that are not yet well determined. They are mainly extremely energetic protons, the most energetic so far observed having energies of more than 10^{20} eV. This number is so large that we have to imagine a single proton with the energy of a fast-bowled cricket ball, a comparison that Ian would have appreciated. GCR penetrate the heliosphere, the region around the Sun dominated by the solar wind, and are affected in various ways by the solar wind. Ian's first paper on cosmic rays (8) proposed a model to explain how GCR are modulated during passage through the interplanetary medium (the solar wind). He showed that there is anisotropic diffusion caused by the fluctuating component of the interplanetary magnetic field, and derived approximate equations for the cosmic ray gas that include an anisotropic diffusion tensor. This implies the existence of a radial cosmic-ray density gradient, which was shown to act like an electric field with a potential proportional to the natural logarithm of the density.

A series of papers with L. J. Gleeson followed. The first (10) developed the above ideas in terms of the effects of convection and scattering of GCR by 'magnetic scattering centres' carried along by a radially moving solar wind in a spherically symmetric geometry. It was shown that GCR behave as though they were being modulated by a heliocentric electric field, in other words by a single parameter equivalent to the potential of such a field. However, this only applies for GCR of sufficiently high energy, when the Reynolds number of the cosmic ray gas can be taken as small.

A later paper (13) developed these ideas in greater detail using solutions derived in paper (12). A single parameter $\varphi(r, t)$ describes the modulation when certain conditions on the current density and diffusion coefficient hold, and is equivalent to the potential of a heliocentric electric field. It is shown that this 'force field approximation' breaks down at energies less than 300 MeV per nucleon for protons and less than 250 MeV per nucleon for α particles. The change in energy of GCR moving from the interstellar medium to positions inside the heliosphere can be deduced from φ. The force field approximation was important at the time, although it has several limitations on short timescales and during high solar activity that do not allow a direct application to the heliospheric transport of GCR. However, the force field model also provides a very useful way to parameterize the shape of the GCR differential energy spectrum near the Earth's orbit. In this context it is still regularly used in studies of the production of radionuclides such as radiocarbon in the Earth's atmosphere (see, for example, Kovaltsov *et al*. 2012) with subsequent application to radiocarbon dating and atmospheric chemistry.

Ian continued to work sporadically on cosmic rays in the heliosphere for many years, including fruitful collaborations with L. A. Fisk, leading to, for example, a paper on testing the approximate equations and solutions described above (17), and work looking at anisotropies of relatively low-energy cosmic rays emanating from the Sun (15). However, at that time Ian's focus was moving outwards into the Galaxy, into the realm where the enigmatic GCR were energized.

Acceleration of galactic cosmic rays

Ian's first paper on GCR energization (22) was to become another classic. The paper extended earlier work on cosmic ray acceleration by shock waves by assuming that cosmic rays are constrained to move diffusively with respect to the background medium, and found that the acceleration can be very efficient. For strong shock transitions in this simplified model, a substantial fraction of the kinetic energy of the gas flow can be converted into cosmic ray energy. Although the assumptions made are not strictly valid in many circumstances, the results showed that very efficient energization of cosmic rays by shock fronts is possible. The presence of diffusion permits a large energy enhancement relative to adiabatic compression, because it becomes possible for particles to be accelerated additionally by a first-order Fermi process (Fermi 1949), in which multiple crossings of the shock front result in a gain in mean energy that is approximately proportional to the shock velocity.

This suggested, for example, that a large fraction of the kinetic energy of a supernova explosion can be converted into GCR energy, not all of which is given up again through adiabatic cooling of the expanding envelope. The demonstration in that paper that the first-order Fermi process can lead to very significant GCR energization created a flurry of activity in the cosmic ray physics community. Ian later published an influential review of cosmic ray acceleration by shocks (23), discussing how shock acceleration can explain observed GCR power-law spectra, describing what a self-consistent nonlinear shock acceleration system should look like, and asking pertinent questions about how particles are injected into shocks.

The first of those papers (22) discussed the nonlinear feedback of the accelerated cosmic rays on the background flow. Ian thought this discussion was too brief, and in a later paper (26) provided 'a more extended and intelligible version'. This work confirmed in detail the earlier conclusion (22) that moderately strong shock waves convert most of their upstream kinetic energy into the energization of cosmic rays. Ian continued to make important contributions to the theory of cosmic rays for many years, for example considering the damping and instability of magnetosonic waves in cosmic ray modified shocks (33), the origins of high-energy cosmic rays (37), and the role of cosmic rays in the emission of soft X-rays from the Coma Cluster of galaxies (44).

Synchrotron radiation

A topic that interested Ian for three decades was the effect of synchrotron radiation on astrophysical plasmas. A 1967 paper with M. Simon (11) showed how the emission of synchrotron radiation via the inverse Compton effect in astrophysical plasmas with a hot, highly relativistic, component could lead to thermal instability. This in turn could develop magnetic-field-aligned filamentary condensations, such as those observed in the Crab Nebula.

A series of papers with R. Lieu and others between 1989 and 1997 analysed the relationship between synchrotron radiation and the inverse Compton effect. Three of these (35, 39, 43) developed a generalized method of equivalent photon scattering to show that synchrotron radiation could be represented accurately as inverse Compton scattering of equivalent photons, and developed an accurate radiative loss rate for particles in non-uniform acceleration. The results could be applied to both laboratory and astrophysical plasmas.

Winds: polar, solar, stellar, galactic

Work on the Earth's magnetosphere always had to take account of the effect of the solar wind on that magnetosphere. Ian soon began to consider the solar wind as an entity in itself, and by extension the winds of other stars. His first paper on solar wind structure was published early in his career (5). This showed that expansion of the solar wind leads to a spiral structure of the solar magnetic field, the presence of this field preventing the solar wind blowing slower than 100 km s^{-1}. At some heliocentric distance of the order of 50 astronomical units (a.u.), a shock transition from supersonic to subsonic flow occurs because of the inward pressure of the interstellar medium. Beyond the shock, a boundary shell forms where charge exchange transfers solar wind energy to outflowing neutral hydrogen. This general picture of the heliosphere is still valid, although modified by subsequent spacecraft measurements and theoretical development. For example, it now seems likely that the termination shock is at 75–90 a.u. The region outside the shock is now labelled the heliosheath, terminated in turn by the heliopause boundary with the interstellar medium.

Ian's next 'wind' study was closer to home (14). It was stimulated by the observation that the escape of helium-4 from the Earth's atmosphere cannot be explained by thermal effects alone. Ian proposed that electrons created by photoionization could escape along geomagnetic field lines at high magnetic latitudes into the magnetosphere, dragging helium (and other) ions with them through charge-separation electric fields. The resulting outward plasma flow would become supersonic; by close analogy with the solar wind, Ian termed this the 'polar wind'. His explanation is still the accepted one.

In an influential review (19) with T. E. Holzer, Ian returned to the general problem of stellar winds and related flows. The review showed that the general theory of steady, radial, spherically symmetric flow provided widely applicable results in discussing stellar, galactic, comet and polar winds. These ideas were applied in a later paper (20) in which an initial description of a galactic wind was attempted, the essential difference from stellar winds being that in the galactic case the gravitating mass and the source of the gas are distributed instead of being concentrated in a central body of relatively negligible size.

Having considered the termination of the solar wind at the heliopause, Ian began a programme of work (with J. F. McKenzie and others) investigating the origin of the solar wind, in particular the high-speed streams that seem to be in equilibrium with their coronal base. A short but influential paper (34) explored the possibility that 'microflares' occurring in the strong magnetic fields defining the boundaries of the chromospheric supergranulation network could generate high-frequency hydromagnetic waves. Dissipation of these waves in the corona could then provide the energy needed to drive the fast solar wind.

These ideas were developed in a series of papers (see, for example, (42)), including more realistic properties such as anisotropic proton temperature, Alfvén wave pressure and a realistic magnetic field. Finally, a comprehensive review paper (45) concluded that 'it seems possible to account for the properties of the fast solar wind reasonably well on the basis of high frequency hydromagnetic wave dissipation in the corona.' Ultraviolet observations of bi-directional plasma jets in the solar chromosphere (41) supported the microflares theory, as well as providing important observational support for the reconnection process described above.

Comets and planets

Even though comets were not Ian's main field of research, his scientific contribution was crucial to the development of comet theory. When the existence of the collisionless bow shock in front of Earth's magnetosphere (caused by interaction with the supersonic solar wind) was confirmed in the early 1960s, Ian had the foresight to predict the possible existence of a similar structure in comets (7). This work can be considered as the pathfinder for burgeoning theoretical studies in the 1970s. It also provided the groundwork for his initiation of the daring Giotto mission to comet Halley, the first planetary mission of the European Space Agency. Two major findings from Giotto concerning cometary plasma dynamics also carry Ian's signature.

(i) The first concerns the acceleration of ions in the extended coma regions of comets Giacobini–Zinner and Halley. The formation of a weak shock because of the mass-loading effect makes diffusive shock acceleration (see above) inefficient. Instead, the presence of significant plasma wave turbulence leads to stochastic acceleration via the second-order Fermi mechanism. This was the first time that second-order Fermi acceleration had been studied in an astrophysical environment. A simple analytical model was developed to demonstrate this point (30).

(ii) The second finding deals with the formation of a diamagnetic cavity in the inner ionosphere of comet Halley (and other comets). The force balance argument using the equilibrium between neutral gas frictional force and the $\boldsymbol{J} \times \boldsymbol{B}$ force of the draped magnetic field was first suggested in 1982 (27) and confirmed by Giotto's deep entry into the inner coma of Comet Halley in 1986 (31).

Again, planetary studies were not Ian's main area of research. However, over more than three decades he made significant contributions to the study of the atmospheres, ionospheres and magnetospheres of the terrestrial and giant planets and many of their satellites. An important early work was a review (with D. A. Mendis) of the satellites and magnetospheres of the outer planets (21). This summarized the properties of these bodies as seen from Earth, but was in several ways a 'preview' of what we might expect to see when interplanetary spacecraft reached the outer planets. Ian was delighted when Pioneers 10 and 11 successfully traversed the Jupiter system in 1973 and 1974, returning the first observations *in situ* of the Jovian magnetosphere for comparison with earlier predictions.

The Pioneer missions were surpassed by the Voyager 1 and 2 missions to Jupiter, Saturn, Uranus and Neptune. Ian became very involved with the interpretation of data returned from the spacecraft during traverses of the magnetospheres of all four giant planets from 1979 to 1989. Several influential papers concerned the characteristics of the hot plasma in the Jovian magnetosphere (24), low-energy charged particles in Saturn's magnetosphere (25), the hot plasma and radiation environment of the magnetosphere of Uranus (29), and the hot plasma and energetic particles in Neptune's magnetosphere (32). Ian would undoubtedly consider the Voyager odyssey to be one of the supreme achievements of space science, as the spacecraft continue their exploration of the heliosphere and heliopause eventually to become our first active explorers of interstellar space.

After his retirement from MPAe in 2001, Ian continued his scientific work and publication for some years. This work included several planetary science studies, the most significant of which was his involvement in a notable review of the plasma environment of Mars in 2004 (47). His final publication in a scientific journal (48) in 2008 used Cassini spacecraft observations to test a theory published earlier by Mendis and Axford to explain the brightness asymmetry of Iapetus and other Saturnian moons.

International science organization

As Ian's career developed, particularly at MPAe, he appreciated more and more how important the international science network is. As a theoretician he had worked in New Zealand, the UK, Canada and the USA, and so had some feel for international science. However, being Managing Director of an institute such as MPAe was on a much higher plane. Having ultimate responsibility for ground-based and spacecraft hardware projects made Ian realize how critical the international linkages and time constraints were for successful completion of these projects, and how disastrous breaks in these linkages could be. Such breaks would usually occur for political and financial reasons rather than for scientific or engineering reasons.

Ian therefore strongly supported the development of international scientific organizations that would facilitate peer-to-peer science collaborations and could bring pressure to bear on national organizations and governments that might be proving difficult. In 1986 he was elected President of the Committee on Space Research (COSPAR) of the International Council of Scientific Unions (ICSU), and served two terms from 1986 to 1994. For the first four years of that time he was also Vice President of the Scientific Committee on Solar-Terrestrial Physics of ICSU.

COSPAR was set up by the UN under the auspices of UNESCO and ICSU after the first Sputnik launches, in an effort to de-politicize space research. As a consequence the USSR and the USA had privileged positions in the COSPAR Bureau (one Vice President each and three Bureau members from each side of the political divide). However, the President had to be from a neutral (usually European) country. Ian was the fourth President and served for two terms, finding that this entailed some delicate governance. It required his attendance at meetings of the UN Committee on the Peaceful Uses of Outer Space in New York twice a year. Ian realized that COSPAR was becoming rather moribund, so during his terms as President he set about reforming it with a new constitution and by-laws, and making it as non-political as possible by introducing personal memberships. The biennial meetings grew to about 2000 participants, and additional specialized meetings (Colloquia) were held to allow small countries to act as hosts. New awards were introduced with the help of sponsors, and COSPAR became a much more active organization.

Ian was particularly interested in the development of European science. In 1986 the European Geophysical Society (EGS) was near to collapse. Ian and Arne Richter considered that the EGS was an important focus for European geophysicists and planetary physicists to counteract the strong influence of the American Geophysical Union at that time. The Copernicus Society was set up within MPAe to be the administrative centre for the EGS, with full-time staff to organize meetings and publish journals and books. In the process, a new constitution and by-laws for the EGS were generated, the financial structure was reorganized, and a bottom-up management structure was developed. This was all very successful, the EGS began to thrive, and the Copernicus Society became a communication centre and conference organizer for other groups such as the International Union of Radio Science (URSI), the International Association of Geomagnetism and Aeronomy, and COSPAR in addition to the EGS.

In 2002 the EGS was formally merged with the European Union of Geosciences to form the European Geosciences Union (EGU). The EGU now has 12 500 members worldwide, and its annual General Assembly attendance has grown from less than 1000 at the EGS annual meeting in 1986 to more than 11 000 in recent years, with attendees from all over the world. Copernicus/EGU has heavily emphasized the publication of open-access journals, a project dear to Ian's heart. Beginning with *Atmospheric Chemistry and Physics* in 2001, Copernicus Publications now publishes 32 open-access journals and is the biggest publisher of open-access geosciences journals in the world.

Ian did not forget his home region of the South Pacific, and, as a founding member, he strongly promoted the Asia–Oceania Geosciences Society (AOGS) with the help of Y. Kamide and W.-H. Ip, to provide a focus for geoscientists in Asia and Oceania. The first meeting took place in Singapore in July 2004 with the full support of the EGU and was a great success, with more than 1000 participants. Ian became the first Honorary Member of the AOGS at the July 2006 meeting, and the AOGS Axford Lecture was inaugurated at that meeting with a presentation by Y. Kamide. The AOGS has established its Axford Medal to acknowledge an individual for outstanding achievements in geosciences, including planetary and Solar System science, as well as 'unselfish cooperation and leadership in Asia and Oceania'. The AOGS held a memorial Axford Colloquium at its July 2010 meeting in Hyderabad, India, to remember and celebrate Ian's achievements.

During the Cold War period (until the collapse of the Soviet Union), Ian made use of MPAe's visitor resources and his international connections to promote collaboration between Western European scientists and their counterparts in the Soviet Union and other Warsaw Pact countries. He thought that science was part of the cultural development of a global society and should as far as possible be kept separate from transient political divisions. After the collapse of the Soviet Union, Ian continued to support struggling scientists in Russia and other Eastern European countries, and funded them to visit and collaborate with MPAe as much as he could.

In New Zealand

1982–85

During his 27 years of employment with the Max Planck Society, Ian took two three-year periods of leave. After eight years in Lindau, he accepted the position of Vice-Chancellor of Victoria University in Wellington, the seat of government and capital city of New Zealand. This gave the family the opportunity to revisit their homeland and in particular the town of Napier, where Ian and Joy had spent their growing-up years. They purchased a large house on the hill overlooking the town and curve of the coastline of Hawke Bay (named by James Cook in 1769 for the Lord of the Admiralty). This was to remain a permanent home for the family and a point of return for Ian in the ensuing years. He was later to receive the rare honour of the Freedom of the City.

At Victoria University, Ian immediately took an energetic approach to improving the physical appearance of the campus. He put in place a vigorous programme of renovation and restoration. This included the relocation of the Music Department from the deteriorating Hunter Building to new purpose-built premises. He was particularly passionate about saving the historic Hunter Building from demolition; it is now the face of the university and an icon

Figure 6. Ian and Joy at home in Napier after his elevation to knighthood in the 1996 New Year's Honours List. (Photograph by courtesy of Hawke's Bay Museums Trust and the *Napier Daily Telegraph*.) (Online version in colour.)

of Wellington. An impressive redevelopment of Te Herenga Waka Marae, a traditional place of welcome in Polynesian culture, was also achieved under Ian's leadership.

On the academic side, he encouraged the science departments to amalgamate into stronger units. The first was the Research School of Earth Sciences, building on Victoria's international reputation in this area, particularly in the field of geophysics. Other groupings involving languages and physical and life sciences were slower to move, but in the end accepted the advantages of the stronger units. Ian initiated two new institutes, the Institute for Policy Studies and the Stout Centre for New Zealand Studies, and was gratified in later years to see that both had been successful in encouraging research activities in important areas and were thriving.

1992–95

During Ian's second three-year leave of absence from MPAe he was able to apply his experience and administration skills for the benefit of his own country. Already a Fellow of the Royal Society (1986), during this time Ian was the recipient of numerous New Zealand honours. These included Honorary Fellowship of the Royal Society of New Zealand in 1993; the 1994 Science and Technology Gold Medal, New Zealand's highest scientific award; and naming as both New Zealand Scientist of the Year and New Zealander of the Year in 1995. Virtually unknown in his homeland at the time, on his being named New Zealander of the Year the headline in the Sunday Star Times was 'Space Man Emerges from Black Hole of Anonymity' (7 May 1995). In the same year he was nominated for the 1996 New Year's Honours List and became a Knight Bachelor in recognition of his services to science (figure 6).

Foundation for Research, Science and Technology (FRST)

During the New Zealand science reforms of the early 1990s, FRST was set up to be a competitive funding agency for all areas of scientific research except those funded through the higher-education channel. FRST's stated mission was 'investing for results from research, science and technology to deliver greater prosperity, security and opportunities to all New Zealanders'. Ian chaired FRST from 1992 to 1995. During that time he did his best to ensure that science continued to progress with an appropriate balance of basic and applied science and technology despite the rather narrow FRST mission statement. Ian commented around this time that, in science as in other areas, 'there are primitive and destructive forces abroad everywhere that are difficult to combat' (38).

The Marsden Fund

Ian developed the concept of the Marsden Fund to counteract the drift towards applied research that was encouraged by the New Zealand science reforms and by FRST policies. The fund was named after Sir Ernest Marsden, a student of Lord Rutherford's and famous for the Geiger–Marsden experiment (and later responsible for setting up the New Zealand Department of Scientific and Industrial Research, which disappeared during the science reforms). It was intended to fund scientific excellence and to permit New Zealand scientists to compete internationally; it was soon extended to include the humanities. Ian designed a scheme for handling proposals that was simple, fair and not bureaucratic, but at the same time was intellectually rigorous. He chaired the fund from 1994 to 1998 and tried to ensure that his vision for the fund was not diluted.

The Marsden Fund is still dominant as far as basic research in New Zealand is concerned in terms of quantity and quality of output and collaborations within New Zealand and abroad. Ian would be pleased to know that the Marsden Fund is still providing for a basic level of 'blue-sky' research in New Zealand, even though he would probably agree with many who wish to see significantly increased funding through this channel.

Ian Axford Fellowships in Public Policy

In 1995 the New Zealand Government established the Ian Axford (NZ) Fellowships in Public Policy. Reciprocal to the Fulbright Awards, they give outstanding mid-career American professionals opportunities to research, travel, and gain practical experience in public policy in New Zealand, including first-hand exposure to the economic, social and political management of the government sector. Three or four fellowships per year are awarded for six months of research in New Zealand. They are named after Ian because he followed New Zealand's most famous scientist, Lord Rutherford, in achieving international status and because of his strong links with and experience in the USA.

Retirement from MPAe and after

Ian continued as a Director at MPAe after closure was avoided for the second time in 1996–97, to help guide the Institute through the changes needed for it to become the MPS in 2004. After his retirement from MPAe in 2001, Ian held professorial positions at several institutes until 2004, including the Pei-Ling Chan Professorship of Physics at the University of Alabama, Huntsville, from 2002 to 2004 and a Regents Professorship at the University of California at Riverside in 2003. From 2000 to 2003 he spent a total of 12 months at Nagoya University, Japan, as a visiting professor, working with a very active group that has strong links with New Zealand, notably in a collaboration called the Microlensing Observations in Astrophysics (MOA) project.

Returning to Napier, Ian became involved in a variety of interests old and new. In 2004 he became Chairman of the Mathematics Centre of Excellence at Auckland University, and Adjunct Professor at the Centre for Radiophysics and Space Research at Auckland University of Technology. His interest in the latter centre came about partly because it was involved with New Zealand's portion of the joint Australia/New Zealand bid to host the international Square Kilometre Array (SKA) radio telescope project. Funding for astrophysical research of any sort is severely limited in New Zealand, and Ian was a strong advocate that New Zealand should take part in this project as a means of stimulating continuing local astrophysical research and education.

Ian was convinced that human-induced climate change was a major threat to the future progress of civilization and that the threat was much worse than was generally acknowledged by governments and even by the innately conservative Intergovernmental Panel on Climate Change (IPCC). Although the IPCC has been instrumental in detailing and publicizing the climate change threat, its rules allow only published or about to be published peer-reviewed research to be considered in IPCC reports, thereby always excluding the most recent and up-to-date findings. Ian worked hard to educate himself about the detailed science of climate change, and he became a strong advocate in government and public service circles for sweeping changes in attitudes towards emissions of greenhouse gases and other aspects of human-induced climate change. He gave presentations to government ministers, served on advisory bodies and wrote newspaper articles about climate change. Unfortunately, as has been the case generally in this very political field, his warnings have not yet been heeded.

Ian's mind was seldom still: his interests were many and varied. A boyhood interest in stamps led to a large New Zealand collection bought at auctions when travelling. Extensive research of the Axford name in Wiltshire and Scotland resulted in a serious study of the origins of freemasonry as well as the family genealogy. Always curious about the countries he visited, he was especially intrigued with all aspects of Russian history and culture, prompted by his friendship with Konstantin Gringauz of the Space Research Centre in Moscow. Ian co-authored a book with a scientist recounting her life in Georgia under Stalin's regime.

During the many years that Ian worked in other countries, he commuted frequently to Napier for family events such as graduations, weddings, birthdays and births of grandchildren. He was interested in the Art Deco architecture of the city, and encouraged astronomy in Napier. In 1998 he opened the rebuilt Holt Planetarium in the grounds of his former high school.

After a diagnosis of bowel cancer in 2007, Ian's life changed. Recuperating from treatment, he was able to relax at his home in Napier, enjoying the company of his family, old friends and former colleagues. Time was spent reading, listening to music, following his favourite sport, cricket, on television, and enjoying the occasional game of chess.

Ian died at home on 13 March 2010. He is survived by his wife Joy and their four children, Paul (Napier), Suzanne (Sydney, Australia), Linda (Napier), and Robert (Wellington). Many personal tributes were received by Joy, and several obituaries were published by colleagues and friends (see below). Three symposia (in Hyderabad, Lindau and La Jolla) were held in memory of Ian and his scientific work.

Ian Axford: an appreciation

In obituaries written by close scientific colleagues soon after his death, Ian is described as 'a towering figure' and 'one of the giants' of space physics and astrophysics in the twentieth century. These descriptions are accurate, but he was also a quiet giant. He never raised his voice, even during contentious discussions. His was the perfect example of reasoned discussion countering emotive personality pressure. He appeared amused by rather than annoyed by histrionic displays. Below the surface, however, he had a strong, perhaps driven, personality. He could not have achieved all he did in scientific research and international science management without a strong inner determination to carry his chosen projects through to successful completion. Ian also had a deeply ingrained sense of fairness and inclusiveness that led him to do his utmost to support those he saw as being poorly treated.

Generosity was another often remarked-on trait of Ian's personality. T. E. Holzer describes (J. Axford, personal communication 2012) how as a research student he felt he was not sufficiently interested in the research he was doing to consider carrying on with a research career. Then Ian wrote his short paper on the polar wind, and turned the problem over to Holzer and P. M. Banks to flesh out. Holzer says, 'Finally, I felt the excitement of doing truly interesting research and of interacting with the most stimulating scientific thinker I was ever to meet.' He continues:

> By the time we decided it was time for me to get my degree and move on, twelve papers had resulted from Ian's fertile imagination and his remarkable generosity and mentoring. Of course, Ian was not even a co-author on some of these papers, and was never the first author, in spite of the fact that it would have been appropriate for him to be the first author on eleven of the twelve papers.

Holzer felt that he learned more from Ian in three years than he was to learn throughout the rest of his career. Many other young scientists had the same experience of Ian's imagination and generosity.

Scientists who worked with Ian were strongly influenced by his general approach to research. This was to describe complex cosmic phenomena with simple but insightful models that underscored the essential physics, and then make 'back of the envelope' order-of-magnitude estimates before proceeding to more detailed analyses. This acute physical insight and uncanny ability for order-of-magnitude estimates was allied with a desire to make everything appear as effortless as possible. The result was a conciseness in his publications that made them very readable on the surface, but very frustrating for students and others needing to work out the details. This has been attributed to the influence of his time in the UK (Zank *et al.* 2010), but may also relate to his New Zealand background. The ground-breaking two-page paper that his compatriot and contemporary, Roy Kerr, published on the rotating-black-hole solution to the general relativity field equations was so concise that it could be considered the ultimate in 'exercises for the reader' (Kerr 1963).

On the occasion of Ian's 60th birthday in 1993, the Axford Colloquium was held at MPAe. Many colleagues from around the world attended and gave presentations on how significantly he had influenced the many fields of research in which he worked. Unveiled at the Colloquium was Ian's birthday present, the naming of Asteroid 5097 as 'Axford'. The name was suggested and the citation prepared by D. A. Mendis. Ian said in his response, 'The asteroid presented by Asoka Mendis was a special treat. I have always wanted 20,000 hectares of my own and even though there is a transportation problem and no grass or air, I can dream of it as a place to roam around and enjoy for myself' (36).

There is no better way of concluding this memoir than with the following passage from an obituary by Ian's long-term colleague and friend Vytenis Vasyliunas (Vasyliunas 2010):

Those of us who were fortunate to know Ian Axford personally will always remember his soft-spoken and calm manner in dealing with anything, whether an intriguing question of physics or a tortuous issue of policy. He had an uncanny ability to grasp the essential aspects of a scientific problem and to present them in an illuminating and inspiring way. The influence of his published work continues to shape research to this day, in areas ranging from the Sun and the heliosphere, through planetary magnetospheres and ionospheres, out to the interstellar medium and the galaxy. The passing of Ian Axford has put the closing period to a broad and exceedingly important chapter in the book of space research.

Awards and honours

Ian received many awards and honours during his long and diverse career. The most significant are listed below.

Awards

1969	Appleton Memorial Lecturer and Award, URSI
1970	Space Science Award, American Institute of Aeronautics and Astronautics
1972	John Adam Fleming Medal, American Geophysical Union
1976	Centennial Fellow, Johns Hopkins University
1987	Tsiolkovsky Medal, USSR Kosmonautical Federation
1994	Chapman Medal, Royal Astronomical Society
	New Zealand Science and Technology Gold Medal (now the Rutherford Medal)
Various	NASA Group Achievement Awards: Voyager (3), Cluster, Galileo

Honours

1971	Fellow, American Geophysical Union
1981	Associate, Royal Astronomical Society
1983	Foreign Associate, US National Academy of Sciences
1985	Member, International Academy of Astronautics
1986	Fellow, Royal Society of London
1989	Member, Academiae Europaeae
1993	Asteroid 5097 named ‘Axford’
	Honorary Fellow, Royal Society of New Zealand
1995	New Zealand Scientist of the Year and New Zealander of the Year
1995–	The Ian Axford Fellowships in Public Policy
1996	Honorary Member, European Geophysical Society
	Doctor of Science, *honoris causa*, Canterbury University
	Knight Bachelor, New Year’s Honours List
1999	Doctor of Science, *honoris causa*, Victoria University of Wellington
	Freedom of the City of Napier, New Zealand
2006	Special Award: first Honorary Member of the Asia–Oceania Geosciences Society
2006–	The Axford Lecture

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The frontispiece photograph was taken in probably the late 1990s and is reproduced courtesy of Joy Axford.

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