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Graeme Reade Anthony ('Bill') Ellis 1921–2011

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Graeme Reade Anthony Ellis (universally known as 'Bill') was a pioneer in the area of low-frequency radio observations. By exploiting Hobart's geomagnetic latitude and the lack of background radio noise there, he was able to make major discoveries at these low frequencies (principally in the frequency range 1–10 MHz). Among the questions he pursued were the propagation/dispersion/reflection of radio waves in the ionosphere and the detection of radio emissions from the Sun, the galactic disk and Jupiter. He built innovative radio receivers and de-dispersers to gain information about the radio sources, for example about the Sun via aurorae and about the influence of Io on the Jovian emissions. It is thanks to Ellis' practical research investigations and clever experimental methods that radio astronomy at the University of Tasmania is today firmly established and internationally recognized.

Family Background

Bill Ellis' family on both his father's and his mother's sides came from Devon and Cornwall in the West Country of England. After an early career in the Royal Navy, his grandfather William Charles Ellis (1864–1958) settled in Launceston in the late nineteenth century where he ran a boot-making business and was later a manufacturer's agent selling shoes. Bill's father, Archibald ('Arch') Reed Ellis (1894–1969), was born in Launceston. At the age of 20 Arch enlisted in the 3rd Field Artillery Brigade of the Australian Expeditionary Force and saw service as a gunner at Gallipoli, landing at Anzac Cove on the first day of the campaign, on 25 April 1915. He was wounded at Gallipoli and returned to Launceston after spending some months in hospital in Egypt. He was discharged from the Army in June 1916 as 'being medically unfit through results of concussion contracted on active service'. After the War, Arch Ellis ran or worked for a number of businesses in Tasmania and Victoria. During the Second World War he rejoined the Army, working with the Rationing Department in Hobart, serving for a period as Acting Director of Rationing. From the second half of the 1940s until his retirement, he worked with the Customs Department.

Bill's mother was Jane Irene ('Rene') Crocker (1893–1951). The Crocker family emigrated to Tasmania in the first half of the nineteenth century and established a successful coach-building business in Launceston that endured for almost a century through several generations. One of the family anecdotes tells of Arch Ellis returning home from the First World War after his discharge from the Army and sweeping Rene off her feet. Rene Crocker and Arch Ellis were married at Lawrence Vale Methodist Church, Launceston on 6 April 1917. There were

two living children from the marriage, Yvonne Barbara (later Blair) (1920–2011); and Graeme Reade Anthony (1921–2011). It was Barbara who 'christened' Graeme 'Bill' despite his three given names, and it was as Bill that everyone knew him for the rest of his life.

Early Days

Bill was born in Launceston on 20 December 1921. He attended Glen Dhu Primary School and then Launceston Technical College, and obtained his leaving certificate from Launceston High School in 1938. Some of his lifelong interests emerged as he grew up—he was always inventing, fixing and making things and experimenting, such as when he mixed his own gunpowder, then tested it beneath the family home in Talbot Road, the inevitable result being an enormous explosion and clouds of black smoke. Or constructing the first of several generations of large model aeroplanes and flying them from Windmill Hill into the valley below, to be rescued by their young creator from the roofs of unsuspecting residents.

Bill was also proud of his teenage efforts in building a plywood and canvas Canadian-style canoe, emulating this many years later with a series of polystyrene and fibre-glass canoes and kayaks, followed by a more ambitious trailer-sailer with son David. Bill's nephew, Martin Blair, recalls one epic Hobart Regatta Day canoe adventure on the River Derwent when, to get back in a strong sea-breeze with a sheet for a sail, they tore through the yacht-race fleet followed by many expletives and raised fists.

Bill's lifelong voracious and eclectic appetite for reading and acquiring knowledge in many diverse fields also became evident in his childhood. Although growing up in a family that was generally business-orientated rather than literary, an exception and inspiration for Bill was his Aunty Lil, Mary Lilian Crocker (BA 1922), his mother's eldest sister and a long-serving, brilliantly gifted teacher at the Launceston Junior Technical High School. In later life, Bill's visits to the lending section of the State Library of Tasmania were regular events as he strode up the stairs, often two at a time, with a large pile of books, then out again with a new selection in what seemed to be a matter of minutes. These weekly or even more frequent outings continued until the last few years of his life, when he finally announced that he had read all the books worth reading in the library and would have to start again on those at home. Bill was also a wonderful storyteller in his own right and his daughter Elizabeth recalls his holding young cousins and friends enthralled by his anecdotes.

Bill as Air Navigator—Second World War Experiences

Bill completed his secondary studies in 1938 when he matriculated from Launceston High School. On leaving school he obtained a position as a cadet draftsman with the Postmaster-General's Department (1939). With the outbreak of war later that year, he enlisted with the Australian Army in Brisbane and was sent for training with the 101 Anti-Tank Regiment at Moggill, Queensland. Prior to joining the Army he had volunteered for the Royal Australian Air Force and he was transferred to the RAAF in 1942, doing his initial air training at Cootamundra, New South Wales—standard procedure for RAAF recruits after the Battle of Britain. Britain's Royal Air Force required Commonwealth pilots to compensate for Britain's huge losses of air personnel and Bill therefore joined the RAF, going to Britain via Halifax, Nova Scotia (Canada) to serve as a navigator. He was trained in Lincolnshire and Wales and then joined RAF Squadron 221. He chose to join Coastal Command rather than Bomber Command as he had always liked the coast and ocean—a decision that may well have saved his life as the losses of airmen from Bomber Command were huge. He was selected as navigator of a Wellington bomber, called 'M' for Mother, for operations in southern Italy and the Mediterranean and Adriatic Seas, along with Welsh-born pilot D. Glyn ('Taffy') Millard, later a medical practitioner in New Hampshire in the USA. They would track up and down the Adriatic every second night on the lookout for enemy ships. Bill said that they would turn around and start on their homeward journey when they saw the lights of Venice; it was a real feat that they brought their plane safely home to base time after time. After their close wartime association, Taffy Millard and Bill became lifelong friends through their correspondence and occasional meetings.

University and Scientific Career

Following the end of the Second World War, in 1946 Bill enrolled for a science degree at the University of Tasmania. (As a returned serviceman his fees were automatically covered.) He obtained a BSc with first class Honours in 1949, his honours project being on the electret, the electrical analogue of the magnet. All of his early mentors, particularly Professors Leicester McAulay, John Jaeger, Edwin Pitman and, later, Gordon Newstead quickly recognized his outstanding mathematical and practical research abilities and potential. It was during his undergraduate years that Bill met Dorothy Helen Taylor, the sister of E. R. ('Dick') Taylor, a fellow student studying civil engineering. The friendship between Bill and Helen blossomed through Bill's visits to the library of the Royal Society of Tasmania, where Helen worked, to check the latest issues of scientific journals—a routine he maintained long afterwards in the library of the Physics Department at the University of Tasmania. Bill and Helen were married at St Peter's Anglican Church, Sandy Bay, Hobart on 23 December 1948. Their union resulted in the birth of four children: Elizabeth (born January 1950); a stillborn baby boy (born November 1951); Susan (born July 1953); and David (born June 1955).

Bill's natural talents led automatically to higher-degree studies and he gained his PhD in 1955 for his thesis entitled 'The Z-Propagation Hole in the Ionosphere', a long-standing problem of the triple splitting of ionospheric echoes. During that period (1950–5) Bill concurrently held the position of Senior Officer in charge of the Ionospheric Prediction Service's research station at Mount Nelson near Hobart, one of several IPS sites maintained throughout the country at that time by the Australian Government. He continued with the IPS until a university career beckoned. In September 1956 Bill was appointed Senior Lecturer in the Physics Department at the University of Queensland, taking up the position in early 1957. However, he did not stay there long. His exceptional research abilities had come to the attention of the eminent radio physicist Dr David Forbes Martyn and it was therefore no surprise that he was appointed to work with Martyn as Senior and then Principal Research Scientist (Upper Atmosphere) at the CSIRO research station at Camden, New South Wales; he held that position from early 1958 to late 1960 (Fig. 1).

Figure 1. Bill Ellis at work, Ionospheric Prediction Service station, Mount Nelson, Tasmania, c. 1954.

In 1959, the chair of physics at the University of Tasmania became vacant on the retirement of Leicester McAulay, who had held the position as the foundation professor since 1927. Bill applied and in December 1959 was duly appointed, but deferred taking up the position until the following year. He then remained with his *alma mater* for the rest of his career. In 1982, the year of his retirement, he was granted the title of Emeritus Professor by the University for the distinction of his work and his contributions to Australia's tertiary education sector. For some years following his retirement, he continued with his research investigations at the University and later at the Ionospheric Station at South Lea near Hobart (the replacement for the original IPS station on Mount Nelson which burnt down in 1959), in association with George Goldstone, his early collaborator from the 1950s. Bill also set up a sizeable array of radio transmitters and receivers in his garden with banks of observing and recording equipment in his home laboratory.

Bill was an inaugural member of the Australian Research Grants Committee, 1966–9. This required him, as one of the principal assessors, to undertake considerable travelling throughout Australia; afterwards he preferred to travel as little as possible, whether for work or pleasure. Before this, however, having been elected a Fellow of the Institute of Physics in London in 1958, he undertook a major overseas lecture and study trip in 1959 at the invitation of the United States Air Force Cambridge Research Center in Massachusetts and including lecturing at Paris, Brussels and Cambridge (UK) and visiting observatories in Denver, Puerto Rico and Boston. Then in 1977 he was one of a group of Australian scientists to make an official visit to the then USSR. His unique type of research attracted a number of internationally renowned astronomers to the University of Tasmania, including Professor Bart J. Bok from the Australian National University and Sir Fred Hoyle. In addition, the attraction of a low-radio-noise environment drew the pioneering American radio astronomer Grote Reber to Tasmania, and having Bill there was an undoubted bonus.

In the late 1950s, Bill was a member of a working group on low-frequency phenomena of the International Union of Radio Science. He was an active supporter of the Australian Institute of Physics and the Astronomical Society of Australia, of which he was president in 1975–6. In 1977 he presented the Australian Institute of Physics' annual Pawsey Memorial Lecture in Melbourne. Bill was also Patron of the Astronomical Society of Tasmania from 1970 for the next two decades.

Bill was an inspirational head of the University of Tasmania's Physics Department and under his leadership the department thrived, growing to about twenty full-time staff. That was deemed large enough to permit the establishment of a second chair, to which one of us (RD) was appointed in 1976 to strengthen the theoretical arm of the school. Bill was a very fair head of department and ensured that all sections of the department received their proper share of funding, for which he fought strongly and whose development he encouraged. However, when he became Deputy Chairman of the Professorial Board (1968–9) he was obliged to take a more detached, encompassing view of the broader interests of the university.

Figure 2. Bill Ellis receiving his AO Order of Australia award with wife, Helen, Government House, Hobart, 1984. Reproduced courtesy of the *Mercury* (newspaper), Hobart, Tasmania.

The same can be said of the period (1970–1) when he was Dean of the Faculty of Science. He occasionally observed that the Physics Department may have suffered while he had these wider duties within the University.

Bill's research was recognized nationally and internationally. He was elected a Fellow of the Australian Academy of Science in 1965, having received the Academy's Thomas Ranken Lyle Medal two years previously. The University of Tasmania awarded him its highest degree, a DSc, in the same year. After retirement he was appointed an Officer in the Order of Australia for 'service to science, particularly in the field of radiophysics' (Fig. 2).

Bill nurtured a large number of graduate students who went on to notable careers in their own right. Amongst that number may be counted: R. Dowden, P. C. Fung, W. K. Yip, R. Haynes, P. A. Hamilton, P. M. McCulloch, D. Nicholl, A. Payne, P. Whitham, H. Cane, A. Klekociuk, D. McConnell and J. Reid. At undergraduate level, he preferred teaching electromagnetic theory and plasma physics, his particular areas of expertise, and students greatly benefitted from his insights in those areas. He involved himself closely with Honours students in their research projects, but at PhD level took a more detached, albeit still committed approach to supervision. In the present-day classification of academic staff as 'teaching only', 'research and teaching' or 'research only', it would be true to say that Bill fell into the latter category, for he always believed that research took priority over teaching; indeed lectures were sometimes cancelled when some new radiophysics phenomenon beckoned and could not wait.

The list of Bill's research publications includes very few multi-authored papers and for the most part his papers have a maximum of two authors. It is not surprising that he did not greatly interact with radio astronomers elsewhere in Australia, for he held a monopoly in the area of long-wavelength radiophysics, whereas elsewhere people tended to work at much shorter wavelengths. Bill always liked to be at the forefront of a research topic. He rarely spent more than a few years on a particular topic, during which time he discovered the salient points and then moved on, leaving the details to his followers. He often commented when receiving a request for a reprint 'that was what I was working on last year'.

In later years, with home duties requiring more attention, Bill was less able to devote unencumbered time to his research and collaborations with colleagues. With the onset of old age and a deteriorating memory, Bill moved with Helen from their home at Nile Avenue, Sandy Bay, a beachside suburb of Hobart, to residential care at Lindisfarne on Hobart's Eastern Shore, and then on to further residential care. He died at ADARDS Nursing Home on 4 February 2011. His wife Helen predeceased him in 2007 and he is survived by his two daughters (Elizabeth and Susan) and son (David).

Scientific Contributions

The common thread that runs through all of Bill Ellis' work is the detection of radio waves at long wavelengths from all astronomical sources and of how they reach the Earth at ground level. These electromagnetic waves arise when charged particles, mainly electrons, are accelerated. One of the main sources of acceleration occurs when electrons are constrained to orbit about magnetic field lines at their natural frequency, the cyclotron frequency. For low-energy electrons, this gives rise to cyclotron emission at that frequency. For ultra-relativistic electrons, one gets synchrotron emission at much higher frequencies. These radio waves travel from their source to the observer through the ionized interstellar medium where they experience frequency-dependent delays and dispersion, and then through the Earth's magnetosphere where they may be subject to reflection and refraction. Dispersion effects are particularly noticeable when observing pulsars as the frequency-dependent delays blur the pulse and limit the bandwidth and hence the sensitivity of the observations. In order to overcome this, electronic equipment, called de-dispersers, are used that split the incoming signal into narrow bands and apply appropriate delays to negate the effect of the interstellar dispersion. Bill and his collaborators were masters of this technique. Thus to obtain a decent signal requires four ingredients: a quiet radio environment, the construction of large-scale antennae, the de-dispersion of the signals following their travel through interstellar space, and reassembling them, through sophisticated electronics, after their unravelling, owing to refraction and reflection from various ionized layers, while passing through the ionosphere. Tasmania provided the first of these, with the advantage of its high geomagnetic latitude. The second came about from Ellis' drive and ingenuity, the huge Llanherne array set up near Hobart Airport being the most visible manifestation. The third involved the clever use of up-to-date electronics for spectrum analysis and the fourth requires an uncanny understanding of ionospheric radio phenomena and how they propagate. The consonance of all of these led to the establishment of radio astronomy as a major undertaking at the University of Tasmania, largely through Bill's efforts. He built a strong team of technical support staff, most notably Gordon Gowland, Kevin Parker and Phil Button who were his right hand men. His major contributions to the fields are divided below into four categories for easier reading and they are linked to the numbered, chronological reference list at the end. It is notable that eighteen of the papers were published in the premier journal *Nature*, and that they are mainly single-authored. That is quite a rarity today, when big projects usually require extremely sophisticated equipment and large teams of researchers working in concert.

Ionospheric/Magnetospheric Physics

The directional properties of Z-echo radio signals, arriving at Hobart from the F layer of the ionosphere near the magnetic zenith, were investigated in the first three papers that launched Bill Ellis' career [1, 2, 3]. He recognized and understood the phenomenon of triple splitting of these (4.5 to 5.5 MHz) signals as due to back-scattering; he was also able, using two methods, to determine the size of the propagation hole through which these signals arrive as being roughly circular with a half-power angular width of 0.8°. He turned his attention next to whistling atmospherics, which travel along lines of magnetic force and depend greatly on the geomagnetic latitude of the observing point [4]; the change of magnetic intensity produces an upper frequency limit for whistler propagation, so that at latitudes greater than 62° whistler frequencies fall within the range 1–10 kHz. Turning back to ionospheric physics, Bill showed that reflection and absorption of extraordinary waves can occur in the vicinity of the cyclotron frequency well above the F region [5, 8], provided the electron density is substantial, and this determines the low-frequency limit for radio-wave propagation; thus observations of cosmic radio emissions much below 1 MHz become problematic. While at the University of Queensland, using records obtained at Hobart, he found that lateral deviations of various modes provide enough information to derive the gyrofrequency and horizontal gradient of critical frequency. He also attributed the continuous component of atmospheric radio noise to emission of Cerenkov radiation by auroral particles and showed that the intensity may be as high as 10^{-21} W m^{-2}, well above the minimum observable range based on techniques used at the time [9].

Building upon observations made with Grote Reber [6], Bill explained how observations of cosmic radio noise below the local ionospheric critical frequency is due to its becoming trapped between the ionosphere and the ground and requires a horizontal gradient of critical frequency in the ionospheric layer [11]. Hence the radiation propagates by hop transmission for large horizontal distances. When Bill was at Camden he used loop antennae and a sky-scanning photometer to find that major radio bursts are associated with strong auroral and magnetic activity and can last for over a day [12, 13, 14, 15]; he also established a correspondence between the noise intensity and the simultaneous red oxygen airglow. By comparing recordings made at Camden, Adelaide, Townsville, Kiruna and Hobart, and using direction-finding vertical loop antennae, he and his co-authors found that the majority of noise bursts (generally from latitudes greater than 50°) arrived simultaneously [16, 17, 18, 20, 22]. They concluded that low-frequency noise may be detected over greatly separated recording stations and that the sources of radio storms are normally stationary with respect to the Earth with signals propagating along hydromagnetic ducts. He went on to examine the propagation of extraordinarily polarized waves in the ionosphere and showed, via ionosonde records, that their features can be explained by reflection of the X-wave as a result of coupling between the E and F regions.

Bill's interest in whistling atmospherics never waned and he continued observing them with ever more sophisticated equipment (which had to be operated far from electrical machinery) [21]. Nor did he cease investigating magnetospheric phenomena associated with the cyclotron motion of electron bunches through the geomagnetic field, which can come in short bursts [34, 37]. They usually propagate through magneto-ionic ducts, and echoes exhibiting fine structure can arrive from the magnetic conjugate point during periods of moderate solar activity [66, 68, 69, 75, 76]. The variation in the probability of observing the echoes from the ground with location, wave frequency and time, for the years 1992–6, was estimated with his long-time colleague, George Goldstone. Last but not least, Bill was deeply involved in the Space-Lab 2 Plasma Depletion experiments [67, 71, 72, 73], which were connected to perturbations in the ionosphere due to the shuttle 'Challenger' firing subsystem engines releasing large quantities of exhaust molecules; the resulting recombination of electrons with ions produced an ionospheric 'hole' constituting an artificial window for ground-based observations. In Hobart this allowed Bill to make high-resolution observations [70] of the galactic background at 1.7 MHz.

Galactic Radio Astronomy

Along with Karl Jansky, Grote Reber is regarded as one of the two founding fathers of radio astronomy. Reber became interested in low-frequency observations and, hearing about Bill Ellis' fine work in Tasmania; wrote to him. He later emigrated and settled in Bothwell, Tasmania. His first collaborative work with Bill resulted in the detection of cosmic signals at long wavelengths [6], using cage dipole antennae since the chances of detection become rarer until after sunspot maximum. This was followed up by locating six discrete radio sources in the region 3 to 10 MHz, using Admiralty FHB twin channel CRDF receivers with phase switching, two of the sources lying near the galactic centre [7, 10]; more pertinently, Bill realized that differences between the spectra can be attributed to absorption of the radio signals as they pass through the galaxy. Soon afterwards, Bill employed interferometric methods to identify Centaurus A, Fornax A and Jupiter as being among the sources [23] and inferred that the relative absence of absorption effects at the low-frequency end implied a low electron density in the intergalactic medium. He used his knowledge of Z-mode propagation (with its associated small ionospheric hole) to obtain greater angular resolution [24] and went on to observe fine structure and derive spectra of galactic emissions near the plane of the Milky Way [26]. He also calculated the attenuation of cosmic radio noise in the F-region [31] and showed that the calculated values of attenuation from electron backscatter (generally less than 0.2 dB) agree well with observation at frequencies below 10 MHz.

In a landmark paper with Fred Hoyle [28], Ellis suggested that the maximum in the radio frequency spectrum at 5 MHz and its observed fall at lower frequencies is due to an ionized layer of gas parallel to the galactic plane. By taking the lowest temperature of this layer to be 10^4 K, just consistent with ionization, they estimated the electron density, the mass of the layer and its rate of radiation in the Balmer continuum, which can be attributed to O and B stars. Then in work with Green and Hamilton measurements were made of the distribution of sky brightness during the winter of 1962, at 4.7 MHz [32, 33, 36]. With a low ionospheric critical frequency, it became possible to cover southern declinations between 20° and 50°. They discovered a pronounced absorption trough, indicating a layer of ionized hydrogen in the plane of the galaxy several hundred parsecs in thickness. They also recorded emissions from two external galaxies, NGC 5128 and NGC 1316, as well as from Jupiter, and concluded that such studies provide a sensitive way of investigating the interstellar medium. Bill found that in the direction of the south magnetic pole, the spectra show intensities that vary as the square of the frequency, as expected for a strongly absorbing interstellar medium [35, 38]. In this way the absorption in the disk at any frequency may be deduced, from which one may calculate the emission spectrum from electrons in the halo outside the galactic disk. With Hamilton he undertook a brightness distribution survey at 4.7 MHz at declinations between -12° and -72° during a period of low solar activity [40, 41] and, finding a region of low brightness along the galactic plane between 200° and 240° longitude, they concluded that the ion density in the plane of the galaxy is about 0.1 m^{-3} and the temperature is roughly 10^4 K. They reported on the brightness profile at frequencies running from 2.1 to 19.7 MHz and attributed the change of the profile with frequency to the absorption of the radiation by ionized hydrogen in the galactic plane. (Near the galactic pole the integrated emission from within the disk is about 1/10 of that coming from outside the disk.)

With the discovery of pulsars by Bell and Hewish, Bill's attention naturally turned to them, and he described techniques for detecting them at low frequencies to a meeting of astronomers [49]. Bill used those techniques (a general-purpose transit radio telescope consisting of a circular filled aperture array of diameter 800 m operating in the frequency range 10 to 25 MHz) in conjunction with pulse integration techniques based on a sonograph audio-spectrum analyser, to detect them. He went on to study the radio emissions from the Gum Nebula [51], averaged to a resolution of 11° in declination and 3° in right ascension, and derived the temperature of the electrons.

Being an expert in instrumentation, he succeeded in developing a time-expansion sweep-frequency spectrum analyser for signals in the

0–3 MHz frequency range [53]. It was based on a standard video tape recorder used in the single frame replay mode and it realised a frequency resolution of 10 kHz together with a time resolution of 0·5 s. This allowed him to compare the dynamic spectra on M87 and on the cold sky near M87 at 1.4 GHz frequency [62] and to determine the galactic emission measure below 16.5 MHz [64].

Jovian Radio Emissions

It was the somewhat surprising discovery during June-August 1961 of Jupiter's decametric emissions that sparked Bill's lifelong interest in that subject [25]. There he identified stronger bursts superimposed on a fairly weak background signal and his results indicated that the radiation is associated with a Jovian magnetic field the axis of which is inclined relative to the rotational axis. By assuming that Jupiter has an exospheric ionized medium, Bill showed that the observed properties of the decametric radio emissions from Jupiter arising from cyclotron motion can be readily explained [27]. Unlike the terrestrial case, the cyclotron frequency is much greater than the plasma frequency and this leads to cyclical Jovian radiation the period of which accords with the rotational period of the surface Jovian markings. He estimated the Jovian polar magnetic field intensity to be about 15 Gauss with a magnetic axis inclined at 10° to the rotation axis [29, 39] and electron density in the ionized exosphere at 1.5 Jupiter radius to be $10^9/m^3$.

Assisted by Peter McCulloch, Bill measured Jupiter's decametric radio emissions [30] at six frequencies between 4.7 and 28 MHz [42]. The variation of mean flux density was found to increase monotonically with decreasing frequency and the spectra were found to contain two components with differing indices. The results indicated that the Jovian magnetic pole lies at about 175° longitude or below; they made extensive use of the Llanherne telescope, the receivers of which were designed to operate mainly below 20 MHz. Their success depended on the low amount of man-made interference in Hobart, the large size of the array and its geomagnetic location [49]. Its design was a three-wire dipole, placed vertically, and it was efficient enough to observe signals down to about 2 MHz. In this way, measurements could be made of the Jovian and solar emissions with a frequency resolution of 5 kHz and time resolution of 5 ms. In that way Bill reported on Jovian radio bursts [50, 52] observed between February and April 1971, many of which had a bandwidth less than 10 kHz and were of short duration; strikingly periodic structure was seen and the bursts were characteristically different from solar radio bursts, indicating a small source region. He concluded that the Jovian S-bursts and their occurrence depended on the orbital position of Io [52]. He further investigated at Llanherne other types of bursts [55, 56, 57], using a series of dynamic spectrographs in which various time scales were involved, and this permitted him to distinguish between different sorts of bursts. The correlation between transient S-bursts and the orbital position of Io for all frequencies between 8 and 30 MHz was easily explained [60] if the electrons generating the S-bursts are confined to the magnetic flux tube intersecting Io, with the electronic energy being derived from the relative motion of Io across Jupiter's magnetic field. Dynamic spectra were recorded on videotape using the Llanherne array and the negative drift in frequency of the S-bursts was analysed [65], again proving to be associated with the position of Io. The electrons are thought to emit coherent radiation in the Doppler cyclotron mode as they travel up the flux tube after being accelerated near the base of Jupiter's ionosphere. In a joint paper with Calvert and Leblanc [74], the authors attributed the equally spaced (30 to 50 kHz) discrete spectral components to adjacent longitudinal oscillation modes of natural radio lasers, because their temporal spacings varied inversely with the observing frequency and they inferred an expansion of the lasing regions caused by the projected motion of Io.

Solar Radiophysics

The radio emissions from the Sun did not escape Bill's attention either. In collaboration with Peter McCulloch dynamic spectrographs on the amplitude, polarization and direction of arrival of radio bursts in Tasmania over two years were obtained [43]; the instruments used included a fixed log periodic antenna directed obliquely into a horizontal reflecting screen, and the results were recorded on film by a camera triggered by the bursts. The regular appearance of frequency splitting of about 200 kHz for a second or two was associated with magnetic effects [44, 45]. Occasionally triple splitting was seen. Diffuse radiation with a positive frequency-time slope was observed to follow fast drift bursts and drift pairs on some occasions [46, 47]. A classification of bursts over the period fromNovember 1975 to March 1976 was described in a series of papers with McCulloch [54, 58, 59]; these comprised striae, split pairs, triple bursts, fork bursts and a variety of ultrafine structure. They were recorded via a broad-band dipole array on magnetic videotapes, requiring appropriate processing and clever analysis after the events. Often the bursts were circularly polarized in either sense, but all components of a pair or triple were always polarized in the same sense. During June 1979 several thousand bursts were recorded, mainly below 57 MHz.

Ellis' last foray into solar radiophysics, during the early 1980s, was done with David McConnell [61]. A new variety of fast-drift storm solar burst, characterized by intensity maxima regularly placed in the frequency domain, was described. The phenomena were recorded on six video tape recorders for ten minutes each day during solar transit and subsequently analysed, either using a 256-channel filter bank spectrum analyser or by a time-expansion sweep-frequency analyser. From observations at frequencies in the range 125 to 150 MHz, Bill found that fast-drift storms were similar to those at lower frequency except for showing periodic intensity maxima or fringes in the frequency-time plane [63]. Fringe separation did change with frequency between 30 to 150 MHz and this was inconsistent with being caused by Faraday rotation.

Bill's Influence and His Legacy

The following extracts from his former students attest to Bill Ellis' consummate skills in experimental physics and the influence that he exerted on a generation of radio-physicists.

Pip Hamilton says that

> Bill Ellis was an ideal head and an inspiring leader. He conveyed exactly the right attitudes to students and junior staff on clear thinking, setting priorities and working hard. He took all his students under his wing, holding weekly meetings of the honours group to discuss their projects—and anything else that Bill wanted to talk about, ranging widely over current hot areas of physics to broader issues in science. He always conveyed a clear emphasis on research as serious and important rather than a casual hobby activity. His interests were wide and penetrating. For example he was greatly impressed in 1960 by the work of T. H. Maiman who developed the ruby laser. Maiman had submitted his seminal paper to *Physical Review Letters*, but the editors rejected it because there were 'too many papers on masers'. Maiman promptly revised and resubmitted the paper to *Nature*—even more selective than *Physical Review Letters*—who published it in a week (T. H. Maiman, *Nature* **187** 493–494 August 6 1960). Ellis recognised the importance of this discovery, and followed developments during 1961. I commenced Physics Honours in 1962, and was invited (told?) by him to build a ruby laser. He had recently obtained a rod of artificial ruby for the core of the project. Duplicating the construction of the first laser was a complex task for a raw graduate in physics, but with clear vision and enthusiastic guidance from Bill the laser was successfully built.
>
> Bill Ellis looked after his students. Towards the end of 1964 a lectureship in Physics became vacant, and he suggested to me that I should apply for it. I did, and was successful. I took up the position at the beginning of 1965, when I had completed two years towards my PhD. The completion of the degree was significantly delayed by this, but in retrospect I admit that Bill's advice was very important. He gave me more advice on my first day in the new job: 'you will be eligible for six months' study leave in three years, and you should begin planning for it now'. I did. Bill continued to mentor my development as a physicist for many years. This included encouraging me to form links with professional colleagues at many places, particularly with those in the Radiophysics Division of CSIRO. He assisted many other young people in this way, and we all owe him a great debt.

John Reid expands on the uncanny skill with which Bill managed equipment. He talks about a Fast Response Riometer that he was to take to Macquarie Island:

> I remember Bill coming into the lab when I was really struggling to get my receiver working and with only a week or so to go before the ship's departure date to Macquarie Island. The pass band was a complete mess. He said 'Give me your tuning tool' and proceeded to tweak up the pass band in about 3 minutes. I had been trying for about a week; *he had magic fingers*. When

> I reported seeing the asymmetric pulsations he said something like 'Yes it is like that. When you create a more powerful instrument, you not only see the same things bigger, you also see completely new things.' He tended to communicate his enthusiasm for his work in a casual way, in the tearoom or in the laboratory. Nobody could doubt his passion or his competence.

Elaborating on this, David McConnell states that

> Bill was pragmatic: he would find the quickest was to get the data he wanted, even if the experimental setup was not sustainable in the longer term. *He did not polish things that did not need to shine*. At first glance his experimental techniques were a bit 'rough and ready'—they always turned out to be ready, and any roughness didn't matter. On many occasions he would point out that students learn, creating order in their heads, and so, according to the second law of thermodynamics, they have to create corresponding amounts of disorder around them. 'It's no good complaining about students being untidy; they are just obeying the laws of physics.'

Andrew Klekociuk reiterates this point:

> What I quickly appreciated was Bill's ability to use simple equations and estimation to get at the interesting part of a problem. We didn't need to do detailed calculations—a ball-park estimate of a quantity was sufficient to progress the conversation. Bill also had a fairly dry sense of humour—he occasionally related the story of the person looking for his lost coin at night under a street light, not because it was dropped there, but because this was the easiest place to look. I was never sure if he was talking about me and my investigations, but it made me think.

Bill's kindliness towards his students is seen from this anecdote by Martin George:

> My most significant personal memory was the day Bill summoned me to his office after the fourth year electrodynamics exam. Bill had set a particularly difficult paper. I knew I hadn't done well and to add to all that, on the day of the exam, Bill through no fault of his own had run out of exam booklets and I had ended up writing my answers on separate sheets of paper which were all gathered up with the other students' exams. When I arrived in his office all Bill said to me was 'Martin... your exam'. Naturally I was most apologetic, explaining that I really only completed one of the three questions and discussed the difficulty I had had. Bill looked up at me, this time with a smile, and said 'Ah... OK. You see, I lost your paper, and I wanted to see how well you felt you'd done'. Bill had effectively got me to mark my own exam and I scored 33%. He made me feel much better, though, by mentioning that everyone else had a similar result.

His personality and supervisory technique is summarized by these two extracts contributed by McConnell and Klekociuk: 'Bill was not a gregarious person. In fact he often seemed gruff or disinterested in interacting. I think this hid a basic shyness. I remember him as a kindly but quiet man.' And, 'Overall he was very much a hands-off supervisor—giving some basic instruction and expecting me to get help from the technical staff or PhD students, or to let him know if I was unsure or stuck.'

These vignettes encapsulate Bill the man as seen by persons he mentored during his career.

Family Life

No portrait of Bill Ellis would be complete without some stories about family life—contributed by his daughters. Elizabeth says that

> as children we were well aware that there were times when we had to be seen and not heard—or not seen and not heard—in order to allow Dad the necessary quiet to get on with his work. But despite the load, he used to say that it was wonderful to be paid for what he considered to be a hobby and that he was extraordinarily lucky to be doing what he wanted all the time. The defining characteristic of all activities with Dad was the speed at which everything happened. He strode ahead of us on bushwalks, and on family holidays it was not unusual to wake up and find everything packed up ready to drive home several days early. This race to get things done, and a low boredom threshold where conventional pursuits or methods were concerned, also applied to home improvements—hired tradesmen were never even contemplated. One example which became legendary was of Dad painting an entire room before breakfast with his favourite matt white paint and an ingenious spray-painting device he had rigged up on the back end of a vacuum cleaner. For a time he was known as 'One-coat Ellis' and we still find items from the family home at Nile Avenue bearing tell-tale spots of white paint.

Susan points out that

> Dad's connection with the wind, clouds, sky and the horizon was innate as well as well honed.

> As children we learnt the names of the different types of clouds, and the wind direction and weather were part of everyday conversation in our family. I remember Dad telling me that, when welcoming a group of visiting astronomers at Hobart airport, they exclaimed in delight at the clear Tasmanian horizon. This love and keen observation of atmospheric events stayed with him for life. Even during the last year of his life, including his 89th birthday just last December, when in the grip of advanced Alzheimer's disease, he still loved to be taken to places with long view lines, big landscapes, places where he could observe the wind in the trees, the movement of clouds.

Bill nurtured the love of science in his grandchildren and the following reminiscences of his grandson, Christopher Shearer emphasizes this:

> Granddad was often to be found upstairs at their home at Nile Avenue, sitting in his armchair. All controls for the various technologies he had rigged up were within arms reach—TV, Betamax, VHS, Tape, CD, 16mm Reel to Reel, plus binoculars and telescope should these be required. We would watch programs and movies he had taped during the week that he thought I'd like. We repeatedly watched Stanley Kubrick's *2001: A Space Odyssey*. We would discuss the notions of long distance space travel, Jupiter and its moons, time travel, astronomy and science. Helping Granddad to construct his home telescopes—wires strung across the front and back gardens, as well as large radio dishes, was a major undertaking. The wire/pole telescope covered half of the back garden, and I was very intrigued by its purpose. We man-handled one large dish into position in the middle of the garden, and wired everything back to his home laboratory. He had turned Granny's ironing and sewing room into the control centre for his radio astronomy research and experiments! I'm sure this all caused Granny to despair at times. I can well recall a number of Granddad's memorable sayings. These include: 'Just like a bought one', referring to one of his repair jobs; 'everything has to abide by the laws of physics'; and 'built like an aeroplane', referring to his beloved 1984 Toyota Camry.

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