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John Gatenby Bolton (1922–1993)

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ABSTRACT. For more than three decades following his optical identifications of the Crab Nebula and first radio galaxies in 1948, John Bolton was at the forefront of radio astronomy and led the way to the discovery of quasars and ever more distant radio galaxies. At both Caltech and at the CSIRO Radiophysics Laboratory in Australia, he was the driving force behind a dedicated group of colleagues and students who continue to build on his many pioneering discoveries in radio astronomy. Bolton was recognized by many honors and prizes including the 1988 Bruce Medal of Astronomical Society of the Pacific.

1. INTRODUCTION

Few scientists have been fortunate enough to initiate a whole new field of research, especially at the start of their scientific careers. Fewer still have done so and also remained at the forefront of the field for the rest of their working life. In a brief period between 1946 and 1949, while still in his mid-twenties, John Bolton isolated the first known discrete radio sources, measured their positions and radio spectra, placed upper limits on their angular size, recognized the non-thermal nature of the radio emission, and made the first identifications, aside from the sun, of radio sources with optical counterparts. The publication of these first optical identifications with a supernova remnant and two galaxies, by Bolton et al. (1949), and the realization of the enormous luminosities implied by the existence of extragalactic radio sources, captured the worldwide attention of optical astronomers. For the first time observations outside the narrow classical optical window had a profound impact on astronomy.

Just over a decade later, in 1960, using a precise position determined with his newly completed interferometer at Caltech, Bolton identified the strong radio source 3C 295 with what was then the most distant known galaxy. A few years later, he played a key role leading to the identification of 3C 273 as the first quasar, and for the next 20 years, working with a variety of students and colleagues, he went on to detect, locate, and catalog thousands of new radio sources and to identify more than a thousand with galaxies or quasars.

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2. THE EARLY YEARS

John Gatenby Bolton was born on June 25, 1922, in Sheffield, England, to John Gatenby and Ethel Bolton (formerly Ethel Kettlewell). His first years were spent in a rural area to the west of Sheffield; then, after age eleven, the family moved to the suburbs to be closer to transportation and to schools.

Bolton's school years reflect an independent spirit clashing with traditional schooling. Both of his parents were schoolteachers. Attempts to send him to school were abandoned, he later recalled, in part due to "my obtuseness," and

FIG. 1—John Bolton demonstrating the fringe pattern from the Parkes interferometer (*CSIRO photograph*).

he was educated at home until the age of eleven. He succeeded in winning a scholarship to King Edward VII grammar school, but his first year was marked by failing his science class, a failure, his father explained, which had nothing to do with his ability. For the next two years he was condemned to the classical stream; but he failed Greek and barely scraped through Latin. His grades were better in English, French, history, and mathematics, which apparently convinced the authorities that he should be studying science and mathematics.

After earning his higher school certificate with high distinction, Bolton entered Trinity College, Cambridge, in 1940, with a sufficient scholarship to be financially independent. As a young man, Bolton's ambition was to attend Naval College to qualify as an engineering officer, serve a commission, and then go into private industry as a naval architect. At Trinity College, he got to know the novelist C. P. Snow, who was the Royal Navy's contact man in Cambridge, and through him, Bolton obtained a Naval Commission. He completed his final exams in May 1942, and a few days later, on his 20th birthday, he reported to the Portsmouth Navy Barracks.

After a week learning to be a naval officer, Bolton finished at the top of his one-month class in naval electronics. He spent the next two years designing and flight testing airborne radar equipment. After the Allied invasion of France in 1944, Bolton was posted to the aircraft carrier *HMS Unicorn* and for the next year he was in the East Indies and then the Pacific. At the end of the war he found himself in Australia, and when the *Unicorn* left for England at the end of 1945, he remained in Sydney to work at various Australian bases in the destruction of classified Lend-Lease equipment.

In 1948, Bolton married Letty Leslie, the widow of P. O. E. T. Leslie, a navigator in the Coastal Command, who was killed in action during World War II. He later adopted Letty's two children, Brian and Peter.

3. THE POST-WAR YEARS

In the early 1930s, while searching for the origin of interference to transatlantic radiotelephone service, Bell Laboratories scientist, Karl Jansky, detected celestial radio emission which he correctly identified with the central part of the Galaxy. Although Jansky's discovery received considerable attention in engineering circles as well as in the popular media, it did not attract particular interest among astronomers. For more than a decade, the only serious followup to Jansky's discovery was by Grote Reber. With an antenna built in his backyard, Reber made a detailed map of the radio noise from the Galaxy, and discovered radio emission from the Sun and hints of several other discrete sources. But, like Jansky, his work had little impact on astronomy.

At the end of the war, a small group of scientists, whose contributions to the development of radar had such a profound impact on the outcome of the war, turned their newly developed techniques toward expanding on the discoveries of Jansky and Reber and the independent wartime discovery of solar radio emission by Southworth (1945) and Hey (1946). In England, J. S. Hey, Bernard Lovell, and Martin Ryle started research programs in radio astronomy. In Australia, J. L. (Joe) Pawsey and E. G. (Taffy) Bowen began a radio astronomy program at the CSIR (later CSIRO) Division of Radiophysics. Bowen, who had been the pioneer of airborne radar work in pre-war Britain, brought the first magnetron to the U.S. in 1940, as part of an exchange of wartime radar secrets. He later became the British liaison officer to the MIT Radiation Laboratory where he developed close friendships with leading American scientists, including Lee DuBridge, then director of the MIT Radiation Laboratory and later president of Caltech. By the close of the war, Bowen was Chief of the Australian CSIR Division of Radiophysics in Sydney.

Following a lead from his naval demobilization office, Bolton went to Bowen looking for a job. He started work at the Division of Radiophysics in September 1946, under the direct supervision of Pawsey, who was the Assistant Chief of the Division and head of the radio astronomy group. Bolton, Gordon Stanley, and Bruce Slee set up receivers at 60, 100, and 200 MHz (or Mc s^{-1} as it was then called) at Dover Heights on the south side of Sydney Harbor. They soon detected powerful noise bursts from the Sun and noted the delay in arrival times at the lower frequencies which they correctly attributed to the outward motion of the source of radio noise moving upward through the solar corona. This important discovery was published by Payne-Scott et al. (1947). Paul Wild (private communication) has commented that this first scientific paper of Bolton lead to Wild's design and construction of the first solar radio spectrograph and to Australian dominance in solar radio astronomy for more than two decades.

But Bolton quickly turned his attention to search for radio emission from elsewhere in the sky. By early 1948, he had observed seven discrete sources using a novel "sea interferometer," based on interference patterns first noticed during the use of wartime radar looking at low elevations over the ocean (Bolton 1948). He determined that each source was unresolved with limits as low as 8 arcmin. Then, Bolton and Stanley made the first determination of the spectrum of a cosmic radio source, demonstrating the nonthermal nature of the radiation (Bolton and Stanley 1948a,b). Subsequent observations made with sea interferometers from Australia and a site in western New Zealand resolved uncertainties in source positions due to atmospheric and ionospheric refraction, and demonstrated that the apparent rapid fluctuations in source intensity were not intrinsic, but were due to local ionospheric effects.

Bolton et al. (1949) obtained accurate positions for four sources, Virgo A, Taurus A, Centaurus A, and Cygnus A. The strongest, Cygnus A, could not be identified with any visible object although they had determined its position to better than 8 arcmin, a remarkable accomplishment for the time (Bolton and Stanley 1948a). But they were able to identify Taurus A with the well-known Crab Nebula, the remains of a supernova event which occurred in the year 1054 A.D. (Bolton and Stanley 1949). Bolton communicated his results directly to Jan Oort, Bengt Strömgren, Walter Baade, and Rudolph Minkowski and was greatly pleased by their enthusiastic response (Bolton 1990).

Both Virgo A and Centaurus A were identified with the

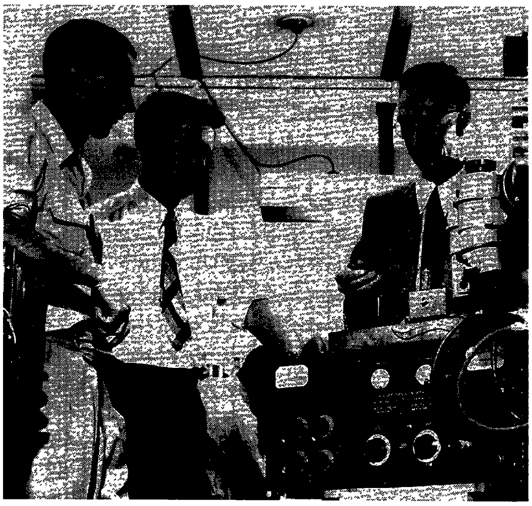

FIG. 2—From left to right, John Bolton, Gordon Stanley, and Joe Pawsey examine their receiving equipment in early 1954 (*CSIRO photograph*).

peculiar galaxies, M87 and NGC 5128, respectively, thus setting the stage for decades of future work in radio galaxy research. Bolton, Stanley, and Slee recognized the implications of placing the "radio stars," as they were then known, far beyond the limits of the Galaxy, and commented in their paper that M87 and NGC 5128 might in fact be "diffuse nebulosities within our own galaxy." They went on to remark, "the possibility of an unusual object in our own galaxy seems greater than a large accumulation of such objects at great distance." It would be several years before the extragalactic nature of "radio stars" was universally accepted. But, as a result of the identification of three of the strongest radio sources with known optically peculiar objects, radio astronomy research, which had been primarily pursued by scientists with backgrounds in radio and electronics rather than in astronomy, began to attract the attention of astronomers and astrophysicists. While Jansky and Reber are properly considered the fathers of radio astronomy, the work at Dover Heights by Bolton and his colleagues perhaps marked the beginning of modern radio astronomy. For the next 30 years, Bolton was to remain at the forefront of extragalactic radio astronomy.

During the following years, Bolton and Kevin Westfold (1950a,b) located the position of the Galactic plane and gave the first convincing evidence of the presence of a spiral arm in our galaxy and the direction of rotation. Later, Dick McGee and Bolton (1954) correctly associated the Sgr A radio source with the center of the Galaxy. Bolton et al. (1954) cataloged more than a hundred discrete sources and discussed the apparent excess of weak radio sources, starting debate about their implication for cosmology that continues to this day.

Although Bolton has been reported to have feuded with Joe Pawsey throughout his years at Radiophysics, Pawsey admired and respected Bolton's accomplishments. In 1951, Pawsey nominated him for the Edgeworth David Medal of the Royal Society of New South Wales citing his "participation in the discovery of radio stars, the investigation as to their nature, and the first attempt to use cosmic radio-wave measurements to give information concerning the structure of our Galaxy." In making the nomination, Pawsey went on to say, "... I consider his scientific contributions over the past few years to be materially greater than any other young Australian physicist, mathematician, astronomer, or meteorologist of whom I know." Later, during Bolton's years at Caltech, he and Pawsey kept up a regular scientific correspondence, with increasing personal warmth over the passage of time.

As often happens in a rapidly developing field of science, there was great competition for funds among the various groups at Radiophysics. Bolton had little tolerance for people and ideas that did not conform with his own strong opinions. In 1953, when it appeared that the Radiophysics Lab could not fulfill his ambitious plans to build a large radio telescope at Dover Heights, Bolton left radio astronomy to help Bowen with the Radiophysics cloud physics program. Until his departure for Caltech in 1955, he pursued a variety of cloud-seeding experiments designed to bring rain to Australian farmers (e.g., Bolton and Qureshi 1954).

4. THE CALTECH YEARS

Although radio astronomy began in the United States, for a decade following the end of World War II, there was relatively little effort made in this country to follow up on the pioneering discoveries of Jansky and Reber. But, as Bolton, Pawsey, Bernard Mills, J. P. Wild, and W. N. Christiansen, in Australia, and Ryle and Lovell, in England, led their groups to a series of remarkable discoveries in solar and cosmic radio astronomy, American scientific leaders began to appreciate that the U.S. was seriously lagging in this important new field of astronomy (e.g., Greenstein 1954). At Caltech, President Lee DuBridge, as well as optical astronomers such as Jesse Greenstein, Baade, and Minkowski, recognized the need to initiate a radio astronomy program to complement their strong optical research with the newly completed 200-in telescope at Palomar. With the advice of Bowen, his old wartime colleague, DuBridge, invited Bolton to come to Caltech to "initiate a program of research in radio astronomy here in collaboration with the members of our physics and astronomy and electrical engineering division on the campus and also with the astronomers of the Mount Wilson and Palomar Observatories."

Bolton took a leave of absence from CSIRO to accept a two-year appointment at Caltech as a Senior Research Fellow. In his letter of appointment, DuBridge told Bolton that, "At the end of two years we would like to explore the question of your future with a definite possibility in mind that it may be mutually agreeable for you to remain with us." Indeed, in 1956, Bolton was appointed Professor of Radio Astronomy at Caltech and Director of the Owens Valley Radio Observatory and resigned his position with CSIRO.

During his years at Caltech, Bolton enjoyed the good cooperation and scientific exchanges with the optical astronomers both at Caltech and at the Mt. Wilson and Palomar Observatories, especially with Minkowski who convinced Bolton shortly after his arrival in Pasadena of the importance of arcsecond precision radio positions. It was, therefore, a surprise to everyone when he suddenly announced in the autumn of 1960, less than a year after the Owens Valley Interferometer went into operation, that he would be returning to Australia at the end of the year. Only later, was it learned that two years earlier Bolton had apparently made a commitment to Bowen to return to Radiophysics to oversee the construction and commissioning of the Parkes 210-ft radio telescope and to direct its scientific program.

The six years at Caltech were remarkably productive. Working largely with student labor, Bolton and Stanley built the two-element Owens Valley Interferometer. With this powerful new facility, Bolton, together with a close knit group of colleagues and students, made a series of extraordinary discoveries in planetary, galactic, and extragalactic astronomy. These included the following.

Jupiter Radiation Belts: Alerted by the apparently high brightness temperature of Jupiter measured by the NRL group at 10 cm, Bolton encouraged the observations by Radhakrishnan and Roberts (1960) of the polarized nonthermal radio emission from Jupiter. These first high-resolution radio images of planetary radio emission led to the recognition of the intense radiation belts surrounding Jupiter, analogous to the terrestrial Van Allen Belts, and played a major role in the planning for future NASA missions to Jupiter.

Galactic Emission and Discrete Sources: Using one of the newly completed Caltech 90-ft antennas, Robert Wilson and Bolton (1960) made the first high-resolution map of Galactic nonthermal radiation and discovered over a hundred new galactic supernova remnants and emission nebulae. Daniel Harris, Bolton's first Ph.D. student, made the first detailed study of the radio spectra of supernova remnants (Harris 1962).

Interstellar Hydrogen: Bolton was one of the first to appreciate the importance of 21 cm absorption measurements to studies of the complex interstellar medium (Radhakrishnan and Bolton 1960). In 1957, Bolton and Wild (1957) realized the possibility of measuring the interstellar magnetic field strength by means of Zeeman splitting of the 21 cm hydrogen hyperfine-structure line.

Radio Source Spectra: The first systematic measurements of radio source spectra for a large number of sources over a wide range of wavelengths were obtained by combining centimeter and decimeter observations at Caltech with observations made at longer wavelengths at Cambridge and Jodrell Bank (Harris and Roberts 1960; Conway et al. 1963; Kellermann 1964). These studies showed the remarkably small dispersion in the spectral index of radio galaxies. The discovery of the sources CTA 21, CTA 26, and CTA 102 by Harris and Jim Roberts and of CTD 93 by Kellermann and Read (1965), all of which were previously uncataloged at long wavelengths, led to the recognition of the class of compact flat spectrum sources (Kellermann et al. 1962; Bolton et al. 1963).

Accurate Radio Source Positions and Identifications: Bolton built the Caltech interferometer primarily to measure accurate radio source positions. The twin 90-ft antennas were initially operated at what was then considered a short wavelength of 30 cm, where the interferometer was nearly free of the effects of confusion which had plagued earlier radio interferometers operating at longer wavelengths. Accurate radio positions were measured for large numbers of radio sources by Thomas Matthews and Richard Read (Read 1963), leading to identifications with distant elliptical galaxies (Maltby et al. 1963) and later with quasars. The recognition by Bolton (1960), that radio galaxies had a remarkably narrow dispersion in absolute magnitude around a median value near -21, led to their use in the Hubble diagram and attempts to determine the cosmological deceleration parameter, q_0. At the same time Bolton (1960) made the first effort to construct a radio galaxy luminosity function and to examine the angular size–distance relation for radio galaxies.

Radio Source Structure: Bolton and Barry Clark (1960) mapped the radio source Centaurus A and discovered the large double-lobe structure extending over nearly ten degrees of sky. Per Maltby together with Alan Moffet (1962), who was then a graduate student working under Bolton's direction, used the Caltech interferometer to show that the double-component structure with dimensions greatly exceeding the associated galaxy that had previously been observed for Centaurus A and Cygnus A (Jennison and Das Gupta 1953) was characteristic of most extragalactic radio sources. Bolton was puzzled by the fact that the largest radio sources apparently contained the most energy, as radio sources should lose energy by expansion and radiation as they age (Bolton 1969), a mystery that was only understood with the later discovery of jets which continually carry the power from an AGN to the outer lobes.

The Identification of 3C 295: A few strong sources remained unresolved on the longest baselines, and it was natural to suspect that they might be very distant. Using an accurate position obtained by Matthews, Bolton (1990) identified 3C 295 with a faint galaxy on a Palomar Sky Survey plate. He told Minkowski about the identification. On his last run on the 200-in before his retirement, Minkowski (1960) measured the redshift of 3C 295 as 0.46, by far the largest then known. Although astronomers such as Milton Humason and Minkowski had spent numerous nights looking for distant galaxies, Bolton's identification of 3C 295 quickly extended the scale of the known Universe by a factor of 3. It would be 15 years before a more distant galaxy was reported. But ever since the identification of 3C 295, the search for more distant objects has concentrated on optically identified radio sources.

The Discovery of Quasars: The first group of radio sources later recognized as quasars were originally discovered in the late 1950s as part of the Cambridge 2C (Shakeshaft et al. 1955) and 3C (Edge et al. 1963) surveys. Some sources remained unresolved on the longest baselines of the Caltech interferometer, which meant that they had angular diameters less than 30 arcsec. Long-baseline radio-linked interferometer measurements by Henry Palmer and his team at Jodrell Bank showed that a few sources, including 3C 48, 3C 147, 3C 196, and 3C 286, appeared to have remarkably small components (Allen et al. 1962). 3C 48 was unresolved, with a diameter less than 0.5 arcsec (Rowson 1963). Encouraged by the large redshift which had just been measured for 3C 295, Bolton, Greenstein, and others at Caltech and Palomar naturally speculated that these very small-diameter sources were even more distant radio galaxies.

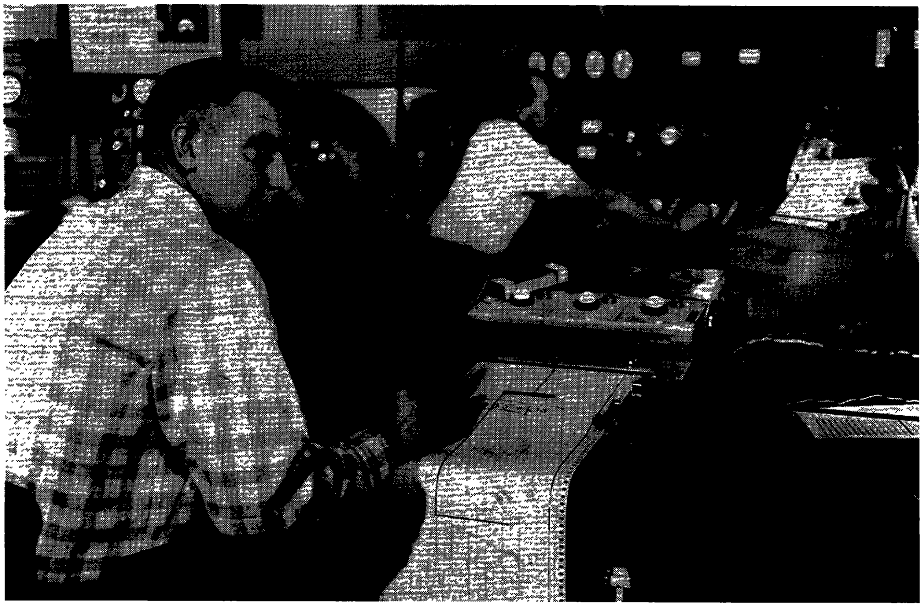

FIG. 3—John Bolton examining data from the Parkes 210-ft radio telescope (*CSIRO photograph*).

An accurate position measured with the Caltech interferometer led to the identification of 3C 48 with a 16th magnitude stellar object in the Palomar Sky Survey. The identification of 3C 48 was reported by Matthews, Bolton, Greenstein, Munch, and Sandage as a late paper at the December 1960 meeting of the American Astronomical Society, but it was described by Sandage, who presented the paper, as a galactic star. Unfortunately, abstracts of late papers were not published at that time, so the only written record of this work is a second-hand report which appeared in the March 1961 issue of *Sky and Telescope*. In view of its small radio and optical dimensions, the detection of both radio and optical variability, and its peculiar optical spectrum, 3C 48 was generally accepted as the first identified radio star (e.g., Greenstein 1963) or "the remnant of a very old supernova" (Greenstein 1961). Indeed, as late as December 1962, Matthews and Sandage (1963) described 3C 48, 3C 196, and 3C 286 as galactic stars. For 3C 48 they remarked, "The lines could not be identified with any plausible combination of red-shifted emission lines."

Two years passed before Maarten Schmidt (1963) determined the redshift of 3C 273. Greenstein then reexamined the old 3C 48 spectrum and quickly recognized that it had a remarkably large redshift of 0.37 (Greenstein and Matthews 1963; Schmidt 1983). In later years Bolton (1990) was to recall that he had suggested from the beginning that 3C 48 had a redshift of 0.37. But, in December 1960 Bolton left Caltech with his family to return to Australia to take charge of the completion of the Parkes 210-ft radio telescope, and for the next few years he had little time to worry about 3C 48 or any other quasistellar radio sources.

5. BACK TO AUSTRALIA

An early Caltech interferometer position of 3C 273 was apparently in error by more than a minute of arc and was tentatively misidentified with a galaxy (Schmidt 1983). The correct position, which ultimately led to the determination of the redshift by Schmidt, was derived from the 1962 August lunar occultation measurements at Parkes as part of a program led by Cyril Hazard who was then working at the University of Sydney. Earlier, Hazard had pioneered the occultation technique at Jodrell Bank in order to provide the precise positions needed for the optical identification of weak radio sources. Overlooking the long-standing feud between senior scientists at Sydney University and at Radiophysics, Bolton welcomed Hazard at the Parkes radio telescope which was ideally instrumented for occultation measurements. John Shimmins and Brian Mackey were assigned to provide telescope and receiver support.

Although the first 3C 273 occultation observed at Parkes in 1962 April gave inconclusive results for the position, it clearly showed the presence of a small component. By the time of the second occultation in August, Bolton and Shimmins had obtained a good position from observations made with the Parkes antenna, and apparently Bolton had made a tentative identification (private communication 1989; Bolton 1990). The extraordinary measures Bolton took to ensure the success of the August occultation are now legendary (Hazard 1985; Bolton 1990, 1994; Robertson 1992). The emersion of 3C 273 from behind the limb of the moon was predicted to occur very close to the zenith angle limit of the Parkes antenna. Not wanting to take a chance on missing this critical observation, Bolton ground away part of the telescope backup structure to gain extra observing time. He stopped all automobile traffic in the vicinity of the telescope and installed a second chart recorder in case the ink jammed in one (a not uncommon occurrence in those days). Following the successful occultation, Bolton and Hazard returned to Sydney with the two recordings on separate airplanes.

A 200-in plate obtained by Minkowski showed the jet as well as the stellar component. The earlier Parkes telescope radio position lay between the stellar component and the end of the jet (Bolton 1990). Hazard's occultation results showed two components, one coincident with the jet and one with the stellar object. Bolton communicated these results to Caltech, apparently via Minkowski who was visiting Australia. Maarten Schmidt then measured a redshift of 0.16 for 3C 273 which untangled the 3C 48 puzzle (Schmidt 1983). The publication of the occultation results by Hazard et al. (1963) appeared with Hazard's affiliation listed as CSIRO instead of Sydney University, leading to a further deterioration of relations between the two organizations then located only a few hundred meters apart on the grounds of the University (Haynes and Haynes 1993).

One of the first observing programs at Parkes was the initiation of a Southern Hemisphere sky survey. Under Bolton's leadership over 2000 radio sources were detected, and accurate positions and flux densities were measured at three wavelengths, 75, 20, and 11 cm (Ekers 1969). For more than a decade, Bolton and a series of colleagues and students refined the survey and made more sensitive observations at additional wavelengths to determine their radio spectra and more accurate positions. Later they extended the survey itself to 11 cm where more than 8000 sources were cataloged in 14 publications over a period of nearly a decade of painstaking work (Bolton et al. 1979). *The Parkes Catalogue of Radio Sources*, which grew out of these surveys, is the basis for nearly all radio source studies in the Southern Hemisphere.

By the late 1960s Bolton's research was almost entirely involved in optical work in collaboration with Margaret Clarke, Jennifer Ekers, Jasper Wall, Jet Merkelijn, and Ann Savage. Optical identifications were found for nearly a thousand sources by Bolton and colleagues in a series of more than 40 papers extending from 1965 to 1982. During this period, he traveled frequently to Caltech to inspect the original Palomar Sky Survey plates and to observe at Palomar and Lick. He took part in the planning and commissioning of the new 4-m Anglo Australian Telescope (AAT) at Siding Springs and became the first chairman of its Time Allocation Committee. He urged the use of an alt-az mount for the AAT, but optical astronomers were not yet ready to depart from the traditional, cumbersome, equatorial mount. Based on his experiences at Parkes and Caltech, Bolton argued for a strong relatively large observatory staff on the mountaintop to support the complex operations of a modern observatory, but again he ran into opposition from the astronomers at the Mount Stromlo Observatory.

An engineer at heart, Bolton designed and built a blink machine capable of simultaneously examining pairs of plates from the UK 48-in Schmidt in two colors. It differed from conventional blink machines of the 1970s in that the plates were viewed with TV cameras which could present the images side by side, or coincidentally with the signal from one reversed. Bolton's machine was a great success not only for research, but for teaching as well, as several people could view the monitor with up to a 100× magnification. Everyone who saw the prototype wanted one, too, and over a period of time he built three machines. Later modifications included interfacing with a computer.

The optical identifications provided a grid of accurately known positions in the southern radio sky, which was used to better calibrate the pointing of the Parkes telescope. This, in turn, led to new optical identifications. His last scientific venture, as Ann Savage's thesis advisor, or as Bolton described it, "her assistant," was to use the UK Schmidt telescope to study the surface density of optically selected quasars as a function of magnitude.

Although he was largely known for his work on radio galaxies and quasars, Bolton was quick to recognize the potential of the Parkes telescope for molecular spectroscopy. Immediately upon learning of the detection of the 18 cm hydroxyl (OH) lines by Weinreb et al. (1963), Bolton unceremoniously displaced the official observer (this author) from his scheduled time on the Parkes Telescope. Using a hastily modified parametric amplifier, Bolton et al. (1964) found a OH weak absorption feature in front of Sgr A. In perhaps the only missed discovery during his long scientific career, Bolton and his colleagues dismissed a heavily sloping baseline as an instrumental effect. Later observations showed that the apparent baseline slope was not an artifact of the makeshift receiver, but in fact the side of a very deep absorption feature, more than ten times stronger than the one they had previously reported (Robinson et al. 1964).

6. THE APOLLO PROGRAM

During a visit to Pasadena in late 1968, Bolton was approached about using the Parkes telescope to support the Apollo Moon landing. With the agreement of Radiophysics Chief Bowen, he personally took charge of the required modifications to the telescope drive and control systems, as well as receivers and other equipment. Initially, Parkes was only to be a backup to the Goldstone antenna for the first lunar landing mission, Apollo 11, and the feed for Australian TV. But, when it was decided to let the astronauts sleep after landing on the Moon, the scheduled time of the first moonwalk was shifted so that the Moon would not be visible from Goldstone, and Parkes was designated as the prime communication link with the astronauts.

When the time came, Neil Armstrong decided to go ahead without sleep, which would have put his moonwalk ahead of moonrise at Parkes. But problems in getting into their spacesuits delayed the astronauts exit from the lunar module until Parkes had acquired coverage, and the world watched most of the first activities on the lunar surface via the telemetry from Parkes.

Pleased with the support from Parkes, NASA asked CSIRO to provide support for future Apollo missions. At the time of the ill-fated Apollo 13 mission, the Moon was too far north for effective coverage from Parkes, and there were no preparations to obtain support from the Parkes telescope. But, following the explosion of the service module fuel tanks, Parkes was called on to receive the very weak signals from the crippled lunar module. Bolton compressed the installation and testing of the specialized Apollo support equipment, which normally took a week, into a few hours. When the spacecraft came into view, Bolton was ready to relay the emergency voice communication back to Houston.

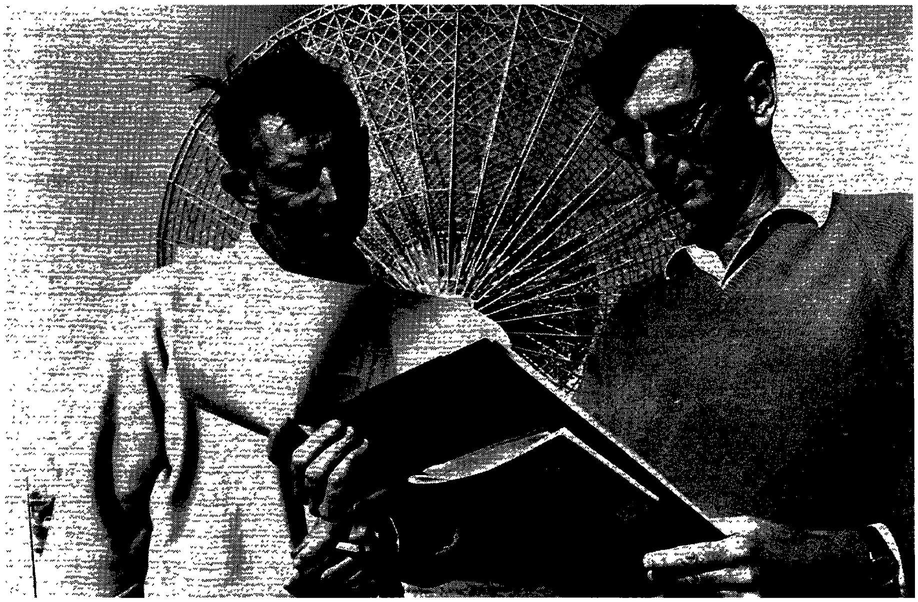

FIG. 4—John Bolton with Paul Wild reviewing preparations for the Apollo landing (*CSIRO photograph*).

Bolton was proud of the role his "budget" radio telescope played in the Apollo program, but he greeted the end of the program with "great personal relief," and looked forward to returning full time to astronomical research. But, his leadership in establishing NASA tracking capabilities at Parkes during the Apollo era set the stage for the successful support of later NASA missions to the outer planets.

In July 1979, Bolton suffered a severe heart attack. Although he found he was no longer capable of long nighttime hours at the telescope, he spent the next 18 months with his associates finishing up the analysis of data already in hand, archiving 13 years of data from the Parkes 11-cm catalog, and bringing the catalog up to date in computer-readable form. He retired to Buderim on the Queensland coast in 1981 and died at his home on July 6, 1993.

7. REFLECTIONS

Perhaps even more important than his published work was Bolton's forceful leadership in the development of new ideas, techniques, and instruments, as well as the encouragement and guidance he gave to his students and younger associates. He was a scientific leader in the true sense of the word: he *led* rather than *directed*. He expected total commitment from his colleagues, more from those who worked for him, and even more from his students; but never more than he was prepared to contribute himself. Whether it was building equipment, maintaining long vigils at the telescope controls, painting antennas, welding steel, pouring concrete, climbing dangerous antenna structures, or digging holes, Bolton was there first, building, observing, painting, welding, pouring, climbing or digging—harder, faster, and better than anyone else. It was hard to keep up with him, but the effort was worth it, especially for the students who literally had to learn radio astronomy from the ground up. His philosophy of education was no doubt influenced by his period of military service which he described as, "a post graduate education in engineering with a diversity which could never have been achieved in civil life and, perhaps as important, experience of working under high stress of immense value later in life." He was very proud that he never received a Ph.D. or D.Sc. degree, and until after his retirement, he stubbornly refused to spend the 5 pounds needed to obtain a Cambridge Masters Degree. He taught himself astronomy by studying past issues of the *Monthly Notices* and the *Astrophysical Journal* during the long nights at Dover Heights while waiting for sources to appear in the beam of his sea interferometer.

Although a professor at Caltech, John Bolton never taught a formal course, perhaps the only Caltech faculty member ever to avoid these duties. But he taught his students and post-docs the meaning of self-reliance, how to build radio telescopes, and how to do research; and he remained an inspiration throughout their careers. All of his students at Caltech and from the Australian National University have gone on to successful careers in astronomy. Six have served as directors of radio and optical observatories in the U.S., Europe, Britain, and Australia. Marc Price and Ron Ekers, his first two students in Australia, currently direct the Parkes Observatory and the Australia Telescope National Facility, respectively. Jasper Wall, a later student, serves as the Director of the RGO. Barry Clark, drawing upon his Owens Valley experience, went on to develop very long baseline interferometry and was largely responsible for the design of the VLA and VLBA. Bob Wilson, one of Bolton's first students at Caltech, later shared the 1978 Nobel Prize for his work on the discovery of the microwave background radiation. Miller Goss, a post-doc under Bolton at Parkes, now directs activities at the VLA/VLBA. Radhakrishnan, who worked under Bolton at both Caltech and CSIRO, later returned to his native India to direct the Raman Institute in

Bangalore. Bolton tcok great pride in the accomplishments of his students and young associates, and was quick to give them credit for their work, unless he felt they were slacking off; then he could be ruthless in overlooking their contributions.

For more than 30 years, Bolton's scientific papers were among the most fundamental contributions to extragalactic radio astronomy, but his impact extended far beyond his published work. Though he was intensely competitive, he was generous in extending credit to others. Some of his most important contributions to astronomy, such as the identification of 3C 295 and his leadership in the work on 3C 48 and 3C 273 leading up to the discovery of quasars, appeared without his name.

Apart from his pioneering investigations leading to the discovery of radio galaxies and quasars, Bolton left other important legacies to astronomy. To catalog the results of the early observations of discrete sources from Dover Heights, Bolton proposed a nomenclature later adopted by the IAU of naming sources by their constellation location. But, the popular use of this system did not extend beyond the most powerful "A" source in each constellation. Years later, when cataloguing thousands of sources with the Parkes radio telescope, Bolton introduced the so-called "Parkes" system where each source was noted by the four digits consisting of the hours and minutes of right ascension and the sign plus two (later three) digits of declination. Unlike other cataloging systems based on consecutive numbering systems, sources could be added later in Bolton's scheme which, following an IAU recommendation, has come into widespread use for naming sources discovered at any wavelength (PASP, 102, 1231).

With the possible exception of Ryle's group in Cambridge, which Bolton referred to as being behind an "iron curtain," he and Letty had close contacts and lasting friendships throughout the world of astronomy. They both enjoyed frequent and lengthy visits abroad, starting with his first trip to the UK, Europe, and the U.S. in 1950. From 1973 to 1979 he traveled extensively as a Vice President of the International Astronomical Union.

John Bolton intensely pursued everything he was involved in, from long nights at the telescope, to building new instruments, and to a variety of sports activities. He enjoyed a competitive game of golf, table tennis, or billiards with anyone who would take him on and was an avid cricket player and fan. Whenever possible, overseas trips were timed to coincide with the Australia–England Test Match in London. Following his retirement, in spite of deteriorating health, he was frequently found on the golf course or experimenting with new body-surfing techniques in the nearby Pacific Ocean.

He had little tolerance for bureaucracy or authority, or what he felt were wasteful expenditures. He resented the overhead charges levied by Caltech on his funds from the Office of Naval Research. Characteristically, he refused to "waste" precious grant money on what he thought to be outrageous page charges in the *Astrophysical Journal*, and so Caltech papers prepared under his leadership appeared in PASP, which at that time had no page charges.

During the course of his career, John Bolton was recognized by many prizes and honors. He was the recipient of the Astronomical Society of the Pacific's Bruce Medal in 1988. He was awarded the 1951 Edgeworth David Medal of the Royal Society of New South Wales, the 1967 Encyclopedia Britannica Gold Medal and Prize for Science (shared with Mills), the American Astronomical Society Russell Lectureship in 1968, and the Gold Medal of the Royal Astronomical Society awarded in 1977. In 1965 he was the first recipient of the Associated Universities' Karl Jansky Lectureship at the National Radio Astronomy Observatory. He was a Fellow of the Royal Society, a C.B.E., a Fellow of the American Academy of Arts and Sciences, Foreign Associate of the U.S. National Academy of Sciences, Honorary Fellow of the Indian Academy of Sciences, and a Fellow of the Australian Academy of Science. Characteristically, disagreeing with the Australian Academy's position on Andrei Sakharov, he resigned from the Academy in 1980 writing, "I have a very strong feeling that scientists or scientific bodies should keep out of politics except on occasions when there is a concrete objective to be gained and where their expertise will be respected."

I was privileged to work with John Bolton as a graduate student at Caltech and later as a post-doctoral fellow at Parkes. In preparing this article, I have been greatly aided by autobiographical notes which Bolton prepared for the National Academy of Sciences, his published memoirs of activities at Dover Heights (Bolton 1982) and Caltech (Bolton 1990), the papers presented at a memorial symposium held at Parkes on December 9–10, 1993 (Goddard and Haynes 1994), and the excellent history of Australian Radio Astronomy by Peter Robertson (1992). Ron Ekers, Director of the Australia Telescope National Facility, and Sally Atkinson, Radiophysics Archivist, and former Secretary to the Radiophysics Division have kindly provided me access to Radiophysics records which include some of Bolton's correspondence and files. John Bolton's sister, Mrs. Jo Wheatley, Mrs. Letty Bolton, Gordon Stanley, Paul Wild, Jesse Greenstein, Don Osterbrock, Maarten Schmidt, Jim Roberts, Barry Clark, V. Radhakrishnan, Marc Price, Jasper Wall, Miller Goss, and others have provided valuable material and comments on the manuscript.

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