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"... for the encouragement of studies and investigations in Science Art Literature and Philosophy ..."

THE ROYAL SOCIETY OF NEW SOUTH WALES

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The Society traces it origin the *Philosophical Society of Australasia* founded in Sydney in 1821. The Society exists for "*the encouragement of studies and investigations in Science Art Literature and Philosophy*": publishing results of scientific investigations in its Journal and Proceedings; conducting monthly meetings; awarding prizes and medals; and by liaison with other learned societies within Australia and internationally. Membership is open to any person whose application is acceptable to the Society. Subscriptions for the Journal are also accepted. The Society welcomes, from members and non-members, manuscripts of research and review articles in all branches of science, art, literature and philosophy for publication in the Journal and Proceedings.

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Editorial

Over the last year or so, the Society has reflected considerably on its role. We are determined to play a large part in the intellectual life of NSW through a range of initiatives, such as the Royal Society of NSW Annual Forum, raising the profile of the Society's very prestigious awards and presenting a range of stimulating, topical talks and discussions about issues that are important in contemporary Australian life. The *Journal and Proceedings* plays an important part in this. It provides a platform for argument and discussion across the breadth of the Society's interests – science, art, literature and philosophy.

To this end, we are fortunate in this issue to have as our leading article an argument for placing a large optical-infrared telescope in Antarctica. Australia has been very active in research in Antarctica and is a world-leader in astronomical research. A strong scientific research programme based in Antarctica, together with other co-ordinated and integrated activities, greatly strengthens Australia's claim to Antarctic territory. Building a telescope in Antarctica would not only help Australia maintain its leading position in astronomy but would be a clear demonstration of the importance of science policy in reinforcing Australia's geopolitical position.

Several other papers have been chosen to give breadth to the edition: radiation treatment of malignant melanoma; a newly-discovered photograph of W.B. Clarke, a towering figure of mid-19th century science in Australia and a vice-president of the Society; and the etymology of dragonfly names.

In this edition, we are reintroducing a "Proceedings" section. For some years, this has been relegated to the *Bulletin*. Information about meetings will still be published in the *Bulletin* but the formal record of the Society's activities will appear in the *Journal and Proceedings*. Of note in this edition of the *Proceedings* are records of the Royal Society of NSW Forum 2011 at which Barry Jones and David Malouf discussed belief and science and the Dirac Lecture, presented by Lord May. There are also two papers, one that demonstrates the effectiveness of the Society's programme in schools and universities and the other a paper written by one of the Society's 2011 Scholarship winners.

This is my last edition, having been elected president of the Society in April. I have enjoyed editing the last four editions of the Journal and would like to express my appreciation to the editorial board for their valuable insights, the anonymous reviewers who contribute greatly to the quality of the publication and, of course, the contributors. I am delighted that the editorship will be passing into very capable hands. Professor Michael Burton, of the Department of Astrophysics and Optics at the University of New South Wales, has agreed to take over as editor of the *Journal and Proceedings*. The Society is most fortunate to have someone of Michael's prominence editing this publication, one of the oldest in the Southern Hemisphere.

Donald Hector
Hon. Secretary (Editorial)

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The Evolving Science Case for a large Optical – Infrared Telescope in Antarctica

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Abstract

The summits of the Antarctic plateau provide superlative conditions for optical and infrared astronomy on account of the dry, cold and stable atmosphere. A telescope on one would be more sensitive, and provide better imaging quality, than if placed anywhere else on the Earth. Building such a telescope is, of course, challenging, and so requires a strong scientific motivation. This article describes the evolution of the science case proposed for an Antarctic optical / infrared telescope, outlining the key arguments made in five separate studies from 1994 to 2010. These science cases, while designed to exploit the advantages that Antarctica provides, also needed to be cognisant of developments in astronomy elsewhere. This has seen a remarkable transformation in capability over this period, with new technologies and new telescopes, on the ground and in space. We discuss here how the science focus and the capabilities envisaged for prospective Antarctic telescopes has also changed along with these international developments. There remain frontier science programs where a 2m class Antarctic optical and infrared telescope offers significant gains over any other facility elsewhere, either current or planned.

Keywords: Antarctica, astronomy, telescopes, optical, infrared.

Introduction

The high Antarctic plateau provides a superlative environment for the measurement of the faint light from distant stars and galaxies. This is on account of the extremely dry, cold and stable air. This permits more sensitive observations to be made, across a wider wavelength range, and with sharper imaging precision, for telescope in Antarctica than if placed in any other location on the surface of the Earth. Constructing a telescope to take advantage of these conditions, however, is a formidable challenge on account of the extreme environment and the logistical difficulties that working on that continent poses. No optical telescope larger than 60cm has yet been operated on the Antarctic plateau through winter months. This was the SPIREX telescope, which ran at the South Pole from 1994 to 1999. This telescope actually worked in the infrared (IR) as it is in this regime that the gains from Antarctic operation are most readily apparent. On account of the extreme cold a telescope on the Antarctic plateau has a similar sensitivity in the IR to a temperate-latitude telescope with a mirror roughly four times larger in diameter for certain types of observation, while also offering the capability to more readily view wide fields with high image clarity. The possibilities for undertaking frontier investigations are thus enticing. For the past two decades exploratory investigations have taken place, first at the South Pole, and then at three sites on the summits of the Antarctic plateau (Domes A, C and F). This effort has been aimed at realising this opportunity by overcoming the technical and logistical challenges that confront the telescope builder. Concurrently with this activity on the continent, off it the science case for building an Antarctic telescope has also been developed, to provide the rationale for why such an endeavour should be undertaken. As astronomical infrastructure has grown elsewhere, both on the ground and in space, and as our understanding of what the right science questions to ask has been refined, following discoveries new telescopes have made, so too has the science case for an Antarctic telescope matured.

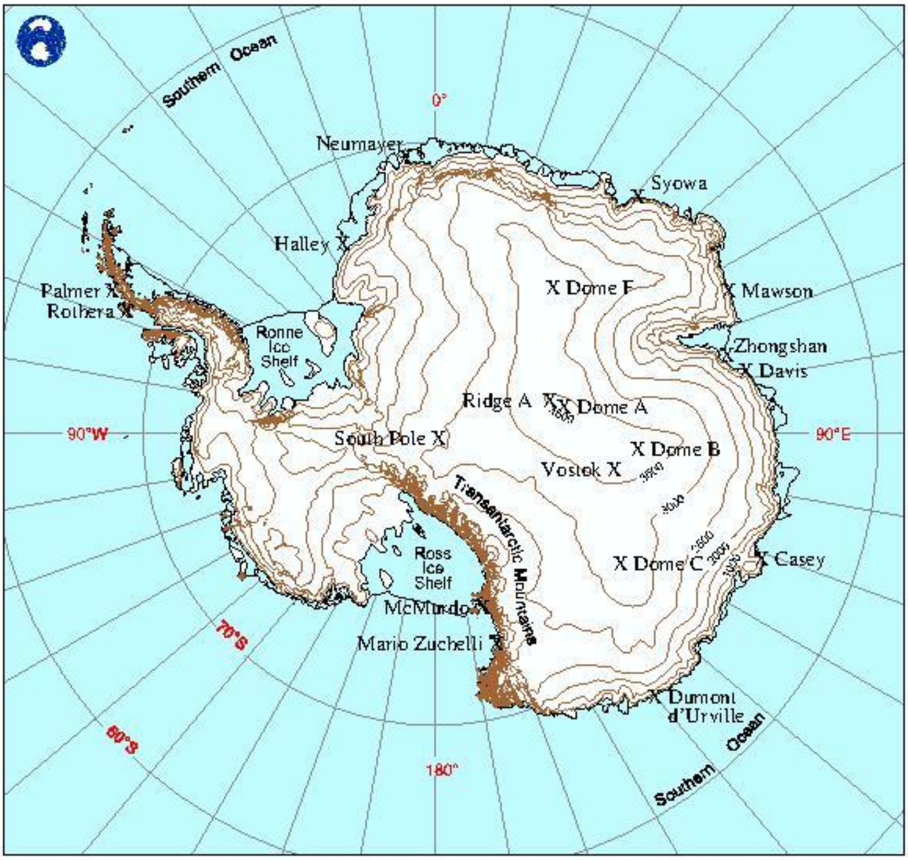

Figure 1. Topographic map of Antarctica, with the location of principal research stations indicated. The high Antarctic plateau runs along the ridge from Dome F to Dome C, through Domes A, B and Vostok. Ridge A lies 400 km SW of Dome A. The South Pole lies on the flank of the Antarctic plateau. Coastal stations supporting high plateau operations are also marked: McMurdo (USA), Mario Zuchelli (Italy), Dumont d'Urville (France), Zhongshan (China) and Syowa (Japan). In addition, the locations of major coastal stations at Casey, Davis & Mawson (Australia), Halley & Rothera (UK), Palmer (USA) and Neumayer (Germany) are shown. Map adapted from a figure supplied by the Australian Antarctic Division, with acknowledgment.

This article discusses this evolving science case, behind the quest to develop optical and infrared astronomy on the continent. A map showing the locations of the principal research stations in Antarctica, including those referred to in this article, is shown in Figure 1.

First words

The first suggestion that the Antarctic plateau might be a suitable place to pursue astronomical observation appears to have come from Admiral Robert Peary, who had led the first successful expedition to the North Pole in 1909 (see Indermuehle, Burton & Maddison 2005). He realised that the long Antarctic winter night (with ~4 months of continuous darkness at the South Pole) would offer new opportunities for astronomical investigation. However, perhaps not unsurprisingly given the heroic endeavours then underway in attempting to even reach the South Pole, he was unable to convince the Director of Yerkes Observatory in the USA, Edwin Frost, to pursue such a course of exploration[1]. The idea did not die though, and eight decades later in 1994, the then Director of Yerkes Observatory, Doyal Harper, was to become the first Director of CARA, the Center for Astrophysical Research in Antarctica. This was the year when the USA began its first major investment in the discipline with the opening of the 'Dark Sector' astronomical observatory at the South Pole. That investment had followed from a decade of modest astronomical experiment at the Amundsen-Scott South Pole Station led by Martin Pomerantz of the Bartol Institute. Pomerantz was to report on these activities at the Astronomical Society of Australia annual scientific meeting in Hobart in 1986 where he said 'one can foresee a burgeoning program of optical, infrared and microwave astronomy being carried out at the South Pole Station during the years ahead' (Pomerantz (1986)). Now, over two decades later, these words are prescient, though the field has developed in ways that Pomerantz could not then have conceived. The South Pole has indeed become a site where frontier measurements in the study of the microwave background radiation from the Big Bang have been made. However, for optical and infrared astronomy this promise has so far been muted. Furtherance of these fields has shifted to the development of sites on the summits of the Antarctic plateau, some that had never even been visited by humans in Pomerantz's day.

Three climatic factors are behind today's activities to develop astronomy on the high plateau – the extremely cold, dry and stable air found there, as first quantitatively discussed by, respectively, Harper (1989), Townes & Melnick (1990) and Gillingham (1993). Harper predicted that the cold air, dropping below -60°C at the South Pole in winter, would make the infrared sky the darkest on the Earth, with sky fluxes up to two orders of magnitude lower than at the best temperate sites, in turn dramatically improving the sensitivity when observations are limited by this sky background. Townes & Melnick analysed measurements which showed that the Antarctic air would hold just a few hundred microns of precipitable water vapour (several times lower than at the best mountain sites). Water vapour in the atmosphere blocks electromagnetic radiation from space from reaching a telescope on the ground across large portions of the infrared and millimetre wavebands, apart from through a few "windows". The much reduced water vapour above Antarctic led them to predict that new windows would be opened for observation of the spectrum.

[1] From correspondence between Peary & Frost in 1912 held at Yerkes Observatory.

Gillingham realised that the strong, but narrow surface inversion layer above the plateau, whereby the temperature could rise by 10-20°C in just a few metres, would present conditions of extraordinary imaging clarity if a telescope could be raised above it, a prediction he called 'super-seeing'.

The subsequent two decades have seen all these predictions verified and their gains further quantified, not only at the South Pole but also on the summits of Dome C and A, where the air is even drier and the depth of the surface inversion layer considerably less. Automated site testing observatories have been built (e.g. Storey, Ashley & Burton (1996), Lawrence, et al. (2005), Lawrence et al. (2009)), the infrared sky brightness at South Pole measured (Ashley et al. (1996)), exceptional seeing conditions found at Dome C (Lawrence et al. (2004)) and high sky transmission found at Dome A in the sub-millimetre and terahertz bands (Yang et al. (2010)). The site testing results, the results of efforts by many scientists, are summarised in the recent review on Astronomy in Antarctica by the author (Burton (2010)). They can be quantitatively summarised through the sensitivity equation for imaging observations made by a telescope, namely that the integration time to reach a given sensitivity level is proportional to the

$$[\text{Sky} + \text{Telescope Background}] \times \left\{ \frac{\text{Image Size}}{\begin{matrix}\text{Sky} \\ \text{Transmission}\end{matrix} \bullet \begin{matrix}\text{Telescope} \\ \text{Diameter}\end{matrix}} \right\}^2$$

In Antarctica the background flux is between 10 and 100 times lower than at good temperate site in the infrared, the median visual seeing above the boundary layer 2-3 times better and the sky transmission is improved right across the infrared and millimetre bands. Indeed, some windows are only opened at all from the ground at the very highest places on the Antarctic plateau. On substituting appropriate gains into the formula above it can be seen that, for equivalent sized telescopes and instrumentation, some kinds of astronomical observation can readily be undertaken in Antarctica two orders of magnitude more quickly than if conducted from a temperate site.

Science cases for Antarctic astronomy

Concurrent with the site testing of the Antarctic plateau has been the writing of science cases for telescopes in Antarctica. While it is easy to say that an Antarctic telescope would be more sensitive than an equivalent telescope placed on a temperate site, building and operating it is, of course, more difficult as well as being more costly. A science case needs to be cognisant of the relevant issues here if it is to contribute to the furtherance of a telescope project. The field itself is also constantly developing, not just with the building of more advanced facilities elsewhere but also in regard to what is considered to be the most exciting and interesting science to pursue. The science case for a new facility thus needs to constantly evolve if it is to remain relevant. Below we discuss the evolution of the science case for Antarctic astronomy as new opportunities presented themselves for the field's development. Five such cases will be précised. The first four of these (Burton et al. (1994), Burton, Storey & Ashley (2001), Burton et al. (2005) and Lawrence et al. (2009a, b, c)) were all published by the Astronomical Society of Australia. The fifth (Epchtein et al. (2010)) grew from these efforts and was prepared by the European ARENA consortium, but with significant Australian input.

The first Science Case of 1994

The first of these science cases (Burton et al. (1994)) was written as Antarctic astronomy began as a field of study in Australia. The 90's had been labelled as the 'decade of the infrared' by the US decadal astronomy plan. At this time infrared (IR) arrays had only recently been introduced to astronomy, providing true imaging quality in the waveband for the first time. New science was thus relatively easy to do. It was simply a matter of having an IR camera and a telescope to place it on. The 4m-sized telescope still reigned around the world, with the construction of the 8m class telescopes just beginning. In space, only the Hubble Space Telescope had infrared capability, and that only extended to a wavelength 2.5μm; Hubble is primarily an optical facility. The science case prepared, written by 20 Australian astronomers, considered a wide-ranging program of science objectives for Antarctic telescopes, placed under five principal themes:

- *Cosmology and the formation of galaxies*: i.e. fluctuations in the cosmic microwave background radiation.
- *The birth of the first stars in galaxies*: i.e. measurement of the cooling lines emitted by the interstellar gas in the IR to millimetre wavebands.
- *The evolution of galaxies*: i.e. measurement of the light from evolving stellar populations which could be probed at 2.4μm, a wavelength where an Antarctic telescope could make exceedingly sensitive measurements on account of the cold. The window here was termed "K_{Dark}" to contrast it with the "K" band window centred at 2.2μm typically used at temperate sites. It was also called the "Cosmological window" in reference to the potential it had in application for such studies.
- *The interstellar medium*: i.e. spectroscopic measurement of the many spectral features emitted by molecules and dust grains across the IR spectral bands.
- *The formation of stars and planets in our Galaxy*: i.e. measurement of the IR continuum emission that occurs from deeply embedded objects, or from disks around forming stars, or from relatively cool brown dwarfs ('failed stars').

The first of these themes became the principal focus for science at the South Pole over the past two decades. Its pursuit requires sensitive measurement of the tiny fluctuations inherent in the cosmic microwave background radiation. The high transmission of the Antarctic atmosphere at millimetre wavelengths, and the extreme stability of its emission, has enabled a series of increasingly sensitive experiments to be undertaken there, led by US scientists, culminating in the installation of the 10m South Pole Telescope (Carlstrom et al. (2011)).

The other science themes envisaged in this first science case focussed on the opportunities for IR astronomy. Given the youthful state of this field at the time, the investigations proposed were in fact little more than a list of the obvious observations that one might make given an IR facility, since these could all be guaranteed to yield new science. The emphasis on the study was more on how the capability to undertake this science might be built up in Antarctica, rather than on undertaking it. The paper envisaged a 4-step process towards constructing Antarctic telescopes:

- Site testing, to quantify the properties of the Antarctic environment that affect astronomy.
- Prototype facilities, to verify that astronomical observations could be

undertaken in Antarctica and that predicted sensitivities could be achieved, while at the same time building experience in Antarctic operation and developing the necessary infrastructure.

- The construction of intermediate scale facilities, capable of undertaking the programs envisaged in the science case. In particular, a 2.5m diameter optical / IR telescope, capable of imaging with 0.2" resolution over wide fields of view, was proposed as the first such facility to be built.
- The construction of major facilities at the best possible sites; i.e. 8m+ optical / infrared telescopes at the highest location on the Antarctic plateau (Dome A, which at that time had not even been visited by humans). Such a project would be beyond the resources of any one country, and international collaboration was envisaged as an essential element if it was to become a reality.

For step 2 of the above, a prototype telescope was operated at the South Pole from 1994-99 (the 60cm SPIREX – the South Pole InfraRed Explorer – see Hereld (1994), Fowler et al. (1998), showing that it was indeed possible to conduct IR astronomy during the Antarctic winter. Two principal kinds of investigation were undertaken with it (see Rathborne & Burton (2005) for a full summary of the science programs done with SPIREX); the study of the galactic ecology using IR spectral features emitted by the gas and dust of the interstellar medium, and the search for disks associated with the formation of stars through the excess flux they would emit at IR wavelengths. These reflected the last two themes listed above in the science case. Figures 2 and 3 show images obtained with SPIREX, illustrating these two science themes.

Figure 2. SPIREX, the South Pole Infrared Explorer, the first infrared telescope in Antarctica, as depicted on a stamp produced for the International Polar Year of 2007. The background (top) is an infrared image at 3.3μm obtained with SPIREX, showing organic molecules (polycyclic aromatic hydrocarbons) in the star forming region NGC 6334 of the southern Galactic plane (from Burton et al. *2000), and (bottom right), the Australian AASTINO autonomous site testing observatory in front of the twin towers of Concordia station at Dome C.*
Image*: Australia Post.*

However one serendipitous project also took place, observation of the impacts of comet Shoemaker-Levy 9 with Jupiter, which took place over a 1 week period in 1994 (Severson 2000); SPIREX was the only telescope in the world where every impact could potentially be seen since Jupiter was continuously visible from the South Pole at the time. Subsequently, the prospects for time domain astronomy – i.e. of making high duty cycle, long-time duration observations – has become one of the most interesting possibilities for future Antarctic telescopes.

A study for an airborne intermediate-scale facility also was undertaken – POST, the Polar Stratospheric Telescope, whereby a 4m-class telescope would be placed into the stratosphere on a tethered aerostat (Dopita et al. 1996). A similar range of science investigations as outlined above was considered, with the focus being the exploitation of the thermal IR regime from 2 to 8μm.

The 2001 Science Case – the Douglas Mawson Telescope (DMT)

The 2001 science case (Burton, Storey & Ashley 2001) accompanied a proposal to the Australian Government Major National Research Facility (MNRF) scheme to construct a 2m telescope in Antarctica, to be called the Douglas Mawson Telescope. The name had, of course, been inspired from the pioneering science venture of the great Australian Antarctic explorer. With the 50th anniversary of Australia's first Antarctic station, Mawson Station, coming in 2004, the event was proposed as a suitable occasion to begin the construction of the DMT.

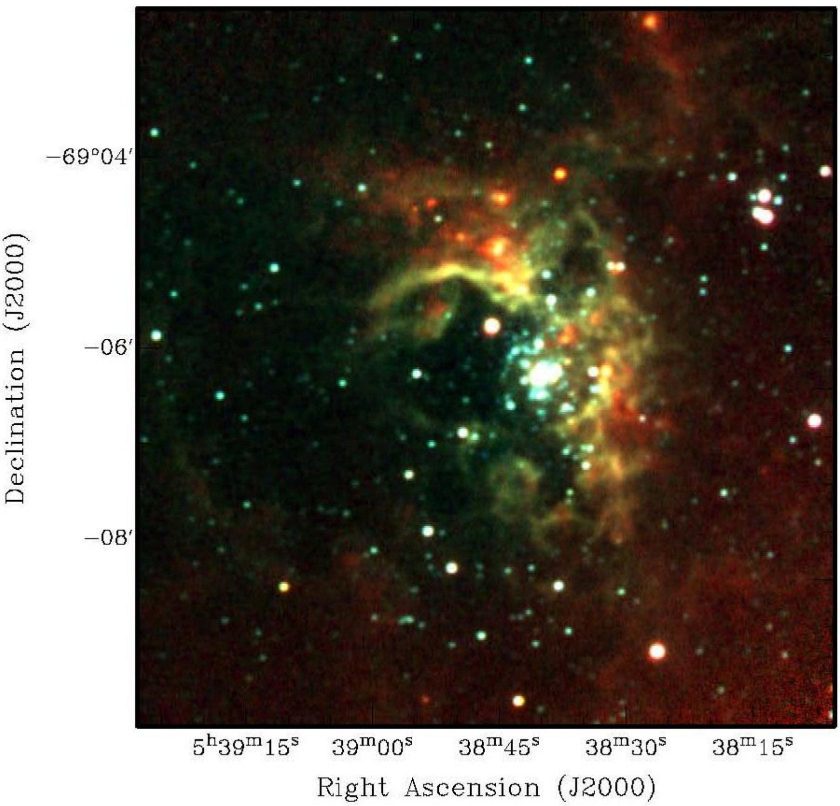

Figure 3. Infrared image of the 30 Doradus star forming region in our neighbouring Galaxy, the Large Magellanic Cloud, as taken by the SPIREX telescope from the South Pole. The red colour shows emission at 3.5µm, with the blue and green showing 1.6µm and 2.2µm band emission imaged by the 2MASS all-sky survey telescope (see Maercker & Burton 2006). When the SPIREX image was obtained it was the deepest ever taken at 3.5µm, despite the modest 60cm diameter of the telescope. ***Image****: Michael Burton.*

to have started, as a field of science, on Mawson's Australasian Antarctic Expedition of 1911-14, with the discovery of the Adelie Land Meteorite on December 5 1912. This was the first meteorite to be discovered in Antarctica and the find was subsequently written up as a scientific paper (Bayly & Stillwell (1923)). While it took nearly 50 years for the next Antarctic meteorite to be found, Antarctica has subsequently provided the majority of all meteorites discovered around the globe, on account of its special geography. The flowing ice sheets over the plateau bring meteorites from all over the continent to 'blue-ice' fields, where the wind ablates the snow, so dropping them. They can then be readily recognised and so collected.

By the time of the 2001 science case a new high plateau station was also under construction, the French-Italian Concordia station at Dome C, where the prospects of 'super-seeing' being attained were high on account of the presumed narrow boundary layer and minimal winds that must exist at that site. Three particular focus areas then presented themselves for a 2m-class telescope:

- *Wide-field, thermal infrared imaging.* For this application, an Antarctic 2m telescope would be as sensitive as the new generation of 8m class telescopes at temperate sites, but with the opportunity of wider fields of view, as well as simpler requirements on instrument design.
- *Continuous observation at 2.4μm [K_{Dark}]*, the wavelength where the background is lowest, then measured to ~100 times less than at temperate-latitude sites. At this wavelength interstellar extinction is also low, allowing one to see through to the centre of the Galaxy.
- *Mid–IR interferometric imaging*, exploiting both the lower sky background and improved sky stability over temperate-latitude sites.

The 2001 science case discussed several illustrative programs that could exploit such advantages, including:

- Near–IR imaging of the environment of embedded star-forming complexes in molecular, neutral and ionized species (e.g. through measuring molecular hydrogen (H2), polyaromatic hydrocarbons (PAH) and hydrogen Br-α spectral line emission).
- Thermal–IR imaging of the embedded stellar population of star forming regions, determining complete population statistics and in particular identifying the youngest members through the incidence of disks around them.
- Near–IR surveys for proto-galaxies and the early stages of star formation in galaxies.
- Micro-lensing studies towards the Galactic centre at 2.4μm, in particular to identify the incidence of secondary lensing caused by planetary systems.
- Mid–IR interferometric imaging of nearby star systems to search directly for proto-planetary disks, zodiacal dust clouds and Jovian-size planets around them.

Notably different from the 1994 paper, the science case had evolved towards emphasising several specific projects of interest, although the telescope was still envisaged as a general purpose facility. Interferometry, while a part of the science case, was not intended for the DMT itself, rather that it would provide a future development direction once a single telescope was operational, by expanding upon it to a suite of 2m-class telescopes. Such an Antarctic interferometer was also discussed in terms of the roadmap towards two proposed space interferometers, the TPF (Terrestrial Planet Finder) and Darwin satellites. These were then under consideration by NASA and ESA (but subsequently abandoned due to cost). A single dish successor telescope to the DMT was also envisaged – the 6.5m ALTA (A Large Telescope in Antarctica) – whose IR sensitivity and image quality would be significantly better than the then-new 8m class telescopes. Unfortunately, news that the DMT proposal had not been funded under the MNRF program was received during a workshop involving the prospective French and Italian collaborators held at the Australian Antarctic Division in Hobart in July 2001. That marked the end of the quest to build the DMT.

The 2005 Science Case – PILOT Pathfinder for an International Large Optical Telescope

In 2004 a Centre of Excellence scheme, administered through the Australian Research Council, was announced by the Government, and this provided the incentive for the next major push for an Antarctic telescope. It was to be called PILOT, the 'Pathfinder for an International Large Optical Telescope', and was proposed as a 2m diameter optical/IR telescope for building at Concordia station at Dome C. The accompanying science case was published in PASA in 2005 (Burton et al. (2005)) and now involved 27 authors. The paper included a detailed performance evaluation for the telescope, calculating sensitivities, imaging quality and survey speeds for a wide range of potential programs from visible to mid-infrared wavelengths, and comparing the Antarctic gains over facilities planned elsewhere for like measurements.

The science case was a comprehensive document, envisaging an observatory mode of operation for the telescope, so catering for the scientific interests of a diverse community. Topics ranged from Solar System studies to searching for the light from the first stars in the Universe. By now, 8m class optical/IR telescopes were common, and the development of the successor to the Hubble Space Telescope well underway (then known as the NGST – the Next Generation Space Telescope). NGST was to be an IR mission. IR missions in space had by now also included MSX and Spitzer, with their significantly better continuum sensitivities in the thermal IR than would be achievable in Antarctica (albeit with lower spatial resolution). The PILOT science case had to be cognisant of the current or planned capabilities of all these facilities, and so it emphasised the wide-field imaging ability in comparison to the deep, narrow-field studies that other facilities might undertake better. The PILOT proposal emphasised four particular science programs, each exploiting a different Antarctic advantage. These were:

- *Probing the early stages of planetary formation*. This required thermal infrared measurements (3-5μm) to search the 'excess' emission produced by a proto-planetary disk surrounding a forming star. Surveys would be undertaken to quantify the incidence and evolution of such disks in star-forming molecular clouds. The cold, stable conditions meant that such measurements would be superior when made from Antarctica than from temperate sites.
- *Revealing the internal structure of stars*, by measuring their surface oscillations, a process akin to the way the Earth resonates when a seismic wave is generated. Such oscillations can be detected by precise and continuous measurement of the photometric fluxes emitted by stars. By following the many modes of oscillations that occur, this allows the internal structure of stars to be probed. The southerly location and the stable atmosphere, in particular the low scintillation noise due to the superb visual seeing (from above the surface boundary layer), made Dome C an excellent site for such measurements.
- *The formation history of galaxies*. This required the direct measurement of the

stellar populations inside other galaxies, rather than of simply global properties (such as of their luminosity, mass and galaxy type) that were commonly obtained in studies of these objects. This, in turn, requires high sensitivity and imaging quality across a wide spectral bandpass, i.e. the determination of spectral colours of stellar groups between the visual and infrared bands, such as [V–K] (the flux difference $F_{0.5\mu m} - F_{2.4\mu m}$). High imaging quality and sensitive infrared measurements are necessary for such observations, as again possible from the Dome C site. By using a tip-tilt secondary mirror, near diffraction limited image quality could be obtained over wide fields of view on account of the seeing quality.

- *The star formation history of the early universe.* This could be probed by following the emission from hydrogen recombination lines with cosmic time. These lines are emitted from the ionized nebulae that surround luminous, massive stars. The Hα (i.e. n=3-2) line, emitted at 656nm, is particularly useful for this purpose as it is red-shifted into the infrared wavebands for galaxies emitting in the first few billion years of the Universe. At a redshift z of ~3 (i.e. about 3-4 billion years after the Big Bang) this light will be observable at a wavelength of 2.4μm, in the K_{Dark} waveband where Antarctic measurements are particularly sensitive due to the extreme cold. Combined with high imaging quality over a wide field of view, the PILOT telescope would be able to measure the star formation rate as a function of epoch and so study its evolution over cosmic time.

The Centre of Excellence proposal also failed to be selected despite strong institutional support within Australia as well as the USA and Europe. On the positive side, this failure to be funded stimulated the European scientists on the proposal to seek support from the European Union. This led to the formation of ARENA – Antarctic Research, a European Network for Astrophysics – funded under the EU Framework Program 6. Over the next few years ARENA developed its own science case for an Antarctic telescope, which we will return to below.

The 2009 Science Case – PILOT Mark II

The next opportunity to pursue support for an Antarctic telescope in Australia came in 2006 through the NCRIS scheme – National Collaborative Research Infrastructure Strategy. Funding emerged for a preliminary design study, which resulted in a comprehensive study of the key engineering issues associated with the construction and operation of an optical telescope in Antarctica [2]. In particular, careful consideration was given to how to overcome the icing problem caused by the super-saturated air within the stable boundary layer, without also degrading the superb free-air seeing. The science case was also developed further, led now by Jon Lawrence. It considered what a 2.4m-sized telescope in Antarctica could now achieve, but the name remained as PILOT (see Figure 4).

The case appeared in three papers published in PASA in 2009 (Lawrence et al. (2009a, b, c)). The number of scientists contributing to it had grown to 43. The first of these papers described the telescope and its capabilities, including the prospective instrument suite, and discussed how observing operations might be conducted. It also overviewed the science case, which had been categorised into

[2] Saunders et al. 2008 describes the telescope in more detail. The website at www.aao.gov.au/pilot provides many further documents relating to this design study.

seven themes[3]. The second and third papers discussed these science programs in detail; Paper 2 dealt with the distant universe, Paper 3 on the nearby universe, with the dividing line between these cosmic regimes drawn at the edge of our local group of galaxies. By now the 8m class telescopes were a mature technology and interest was high in the next generation of optical facilities – the so-called extremely large telescopes (ELTs) – and the capabilities they would bring. Furthermore, the NGST had matured into the 6.5m JWST – James Webb Space Telescope – and construction was underway. Another, more modest thermal IR survey satellite was about to be launched (WISE – the 40cm diameter Wide-field Infrared Survey Explorer). SOFIA (Stratospheric Observatory For Infrared Astronomy), NASA's 2.5m telescope carried by a 747 aircraft, was nearing readiness. When flying in the stratosphere the atmospheric transmission experienced would be superior to even Antarctica. The area of unique parameter available for a 2m class telescope in Antarctica thus had diminished further, despite the advantages over temperate-latitude sites. However, there were still clear areas where it would be competitive with any other facility. Indeed, the limitations of the next generation facilities, which were also becoming apparent as their designs matured, presented new opportunities for future Antarctic telescopes as well.

Four specific science projects from the PILOT science case were highlighted in the presentations made to the NCRIS review panels, and these we outline below. They centred around the use of the three instruments proposed:

(i) a wide-field, seeing limited optical imager,
(ii) a wide-field, near-infrared imager (i.e. from 2-5μm) and
(iii) a wide-field, mid-infrared spectroscopic line imager (i.e. from 8-30μm).

A fourth instrument, a 'lucky imaging' camera, was also considered for commissioning the telescope. The rationale behind this instrument suite was to maximise the scientific possibilities given the competition elsewhere. The optical cameras utilised the exceptional seeing whereas the near-IR camera exploited the low background and image quality over wide fields. In the mid-infrared it would not be possible to compete with space-based instrumentation for broad band measurements, due to the vastly lower thermal background experienced by a cryogenic telescope in space. However, the space telescopes would not have spectroscopic imaging capability, so keeping that as a niche for an Antarctic instrument.

(iv) The first of the four science focus areas was to map the cosmic web of galaxies, whose structure results from the dark matter and/or dark energy which dominates the composition of the Universe. It requires the measurement of the ellipticities of a very large sample of weakly gravitationally-lensed galaxies. Their statistically-averaged orientations can then be used to probe the evolution of the galaxy power spectrum with red-shift and hence to derive the equation of state of the Universe. The key to doing this with an Antarctic telescope is the imaging quality possible from the high plateau. Over wide fields of view the seeing attainable, of 0.2–0.3", is well matched to the typical angular size of distant galaxies. The time required to determine the orientation of a Galaxy in this limit depends on the 6th power of

[3] These were: (i) first light in the universe, (ii) the assembly of structure, (iii) dark matter and dark energy, (iv) stellar properties and populations, (v) star and planet formation, (vi) exo-planet science and (vii) solar system and space science.

the angular resolution, so providing a significant advantage for Antarctica over telescopes on temperate sites, where the seeing is 2–3 times worse.

(v) The second project was to search for the earliest evolved galaxies, i.e. with stellar populations resembling those found in galaxies at the current epoch, where the integrated light is dominated by normal (i.e. solar-like) stars. In the optical band, imaging of distant galaxies means viewing rest-frame UV wavelengths, whose light is dominated by a few, extremely rare but very massive stars, so providing a biased view of the galaxy. This project required observation in the infrared rather than the optical, as this is where the red-shifted light of normal stars would dominate a distant galaxy's light output. It also required a wide field of view, with high angular resolution, to overcome cosmic variance and to identify galaxy types from their morphology. A PILOT 'deep field' was proposed for the wavelength of 2.4μm [K_{Dark}], where the Antarctic sky is darkest and the gains over corresponding measurements from temperate sites the greatest. Such a survey would go ~2 (photometric) magnitudes deeper than any other survey contemplated for this wavelength. Moreover, 2.4μm is also the longest wavelength where truly wide-field, sensitive imaging can be obtained (the thermal background at longer wavelengths leads to much reduced sensitivity), so is the waveband of choice for probing furthest back in cosmic time in such surveys.

(vi) The third of the key projects ('first light in the Universe') was to search for gamma ray bursts (GRBs) emitted at high redshifts (i.e. z~6–10; the first few hundred million years after the Big Bang). Such GRBs, if they exist, must be probes of the 'first light' in the universe, being produced by the supernova explosions marking the death of the very first stars (which, being extremely massive, must also have very short lifetimes, of order 1 million years or less). Such distant GRBs can only be seen at thermal infrared wavelengths as their light is red-shifted out of shorter wavelength bands; i.e. at 3μm and beyond. In this project PILOT would be used to follow up satellite detections of GRBs, to search for those only emitting in the thermal IR. The increased sensitivity here compared to temperate telescopes makes Antarctica a compelling place for undertaking such an experiment. Cosmological time dilation, which results in such a burst appearing in the IR ~1 hour after the gamma rays themselves are detected, also ameliorates the technical challenge; the telescope only needs to be ready to respond when a GRB is announced, not actually observing. Of course, such distant GRBs might not actually exist in the universe; we do not yet know when the first stars formed and are only presuming what their form might have been. However, the potential for fundamental discovery made this an enticing experiment to conduct.

(vii) The fourth of the PILOT headline projects was to unveil the molecular medium of our Galaxy, by conducting a spectroscopic imaging survey of two of the lowest excitation lines from the hydrogen molecule. These are emitted in the thermal infrared (at 12μm and 17μm, respectively). Despite being the dominant molecule in space, molecular hydrogen cannot generally be seen directly unless it is warmed to temperatures of a few hundred degrees.

Even these lowest levels are barely be excited in the typical environment of molecular clouds in space, and their emission occurs in parts of spectrum difficult to observe in from temperate latitudes, on account of poor transmission and high sky background[4]. The thermal infrared has not been accessible for large scale spectroscopic mapping surveys before. PILOT would have been able to image the molecular medium of our Galaxy through the infrared molecular hydrogen lines with a spatial resolution of ~2", nearly two orders of magnitude better than the best large-scale maps of the southern galactic plane obtained at millimetre wavelengths of the carbon monoxide (CO) molecule (the next most abundant molecule in space, but a factor ~10^{-4} less common). The Antarctic advantage for such a survey lies in the improved atmospheric transmission, due to the low water vapour, the cold temperature and the stability of the sky emission, which makes the corresponding measurements much more sensitive there than if made elsewhere.

However PILOT Mark 2 also failed to be supported by the review panel, with the recommendation being that the project required further international collaboration. While the NCRIS scheme had allowed the concept to be developed further than before through funding the preliminary design study, in the end the final evaluation process ranked the development of one of the planned extremely large telescopes – the GMT (Giant Magellan Telescope) – as a higher priority for investment. PILOT thus failed to proceed to the full design stage.

The 2010 Science Case – the Polar Large Telescope (PLT) and ARENA

The final science case described in this saga comes from that developed by the European ARENA consortium. This network of European institutions (together with the University of New South Wales) had been brought together through their involvement in the first PILOT proposal to the ARC Centre of Excellence scheme. European Union FP6 funding allowed ARENA to hold a series of workshops over the period 2007-10, ultimately recommending that a telescope based on the PILOT design – PLT (for Polar Large Telescope) – be built at Dome C (Epchtein et al. (2010)). The principal change from PILOT was not to include the optical performance as part of the design driver because that imposed significant cost penalties on an IR-optimised telescope. Wide-field, seeing limited, continuum and spectroscopic operations in the infrared were considered essential. PLT also increased the focus on time monitoring projects compared to the PILOT science case.

The PLT science case (Burton et al. (2010)) had three key program areas: (i) first light in the universe, (ii) exo-planet science and (iii) galactic ecology. These paralleled much of the PILOT science case. Deep infrared imaging surveys were given particular emphasis, such as the K_{Dark} galaxy deep field. Exo-planet science also received a greater focus than for PILOT, through both transit and micro-lensing techniques. Rather than undertake surveys to search for exo-planets, however, these programs were regarded as

[4] There is also a line at 28μm, coming from the very lowest excited level of H_2, but this is not detectable, even from Antarctica, because the atmosphere is opaque at this wavelength.

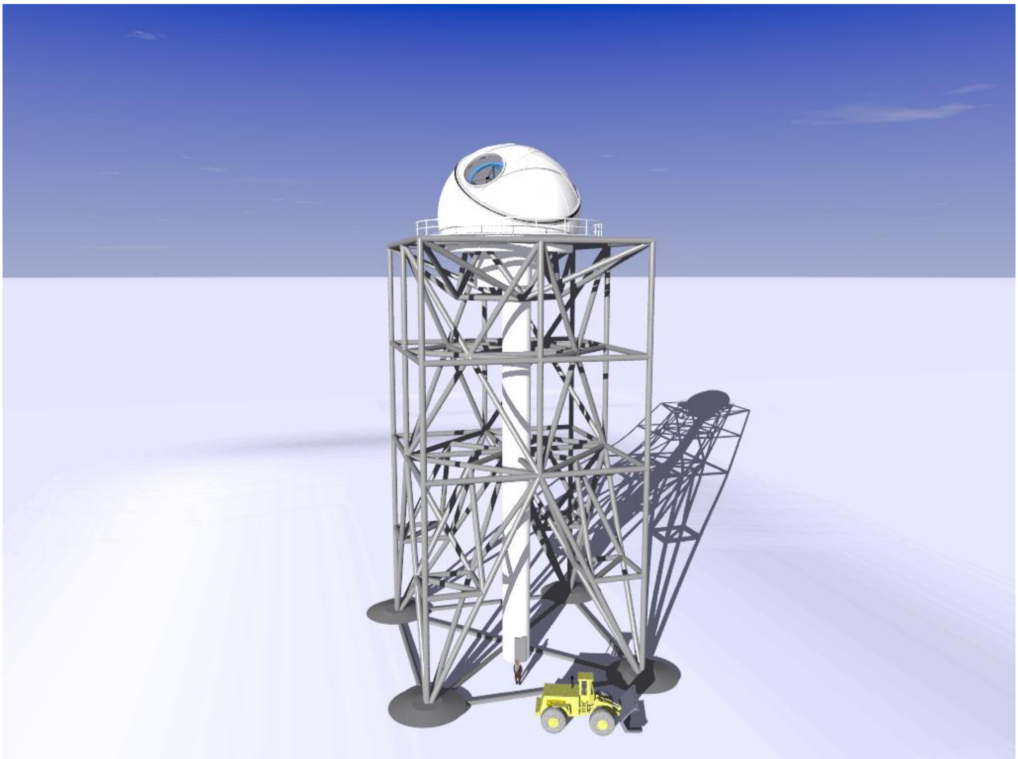

Figure 4. Design for the 2.4m PILOT telescope at Dome C, the Pathfinder for an International Large Optical Telescope (see Saunders et al. *2008). The telescope has a callote-style dome in which the temperature and humidity can be controlled and is placed on a ~30m high tower to raise it above the turbulent boundary layer which generates most of the astronomical seeing. Image Andrew McGrath (AAO).*

alert-mode projects, following up on detections made elsewhere in order to determine physical characteristics of exo-planet systems. The ability to undertake high cadence measurements from Dome C while the ARENA proposal for PLT passed through its initial reviews it too failed to be funded for full design by the European Union.

Summary and conclusions

An intermediate sized optical / infrared telescope has yet to be funded for construction in Antarctica despite its scientific potential. The reasons go beyond the science it could do, of course, and involve the politics of funding as well as human sociology. Beginning a truly new venture in the face of established competition is simply hard. Antarctica is a challenging place, and many people still find it hard to imagine that frontline facilities can be built there, despite the success of instruments like the 10m South Pole Telescope.

Nevertheless, despite the travails of DMT–PILOT–PLT there remain two current projects aimed at building a 2m-sized telescope in Antarctica. One is led from Japan and the telescope would go to the Japanese station at Dome Fuji. The other is led from China and would go the new Chinese Kunlun station, now under construction at Dome A. This latter project has advanced the furthest yet. It is under consideration for full funding in the Chinese Government's 12th 5-year plan. Called KDUST – the Kunlun Dark Universe Survey Telescope – it would be a 2.5m diameter IR-optimised telescope . As the name suggests, the science focus is on wide-field infrared surveys of distant galaxies in order to constrain the equation of state for the Universe (Zhao et al. 2011). A number of prototyping astronomical experiments are being currently being developed for Dome A, including a set of three 0.5m optical/IR telescopes known as AST3 (Yuan et al. 2010). A 5m THz frequency telescope (DATE5) is also under consideration for funding at Dome A as part of this same effort.

The PILOT science case has also been re-visited by Mould (2011), who considered further the cosmological applications of a deep, wide-field survey in the infrared K–band (2-2.4μm). It would be able to probe the so-called dark-ages (i.e. the era before stars appear in the first few hundred million years after the Big Bang, in the redshift range from $z=6$ to as far as $z=25$), searching for any objects which might contribute to the ionization of the atomic gas then pervading the universe (as produced in the recombination event that also resulted in the cosmic microwave background as the universe became transparent to radiation). In other words, the survey could search for signatures from the formation of the first massive stars. With a dedicated survey lasting over perhaps 5 years a steradian could be imaged; i.e. about 10% of the sky if the focal plane could be filled with IR arrays, a more ambitious instrument than had been envisaged for PILOT. Only the proposed WFIRST (Wide-Field Infrared Survey Telescope) satellite could provide any competition to the quality of data such a survey could yield. Mould's paper also noted that such a survey could be undertaken by the KDUST telescope as well as by PILOT.

Regardless of when and where in Antarctica an optical / infrared telescope may be built, the work of the past decade has clarified the science it should do and the capabilities it should have. Sensitive, wide-field surveys with high-angular resolution in the infrared, in particular in the K_{Dark} window at 2.4μm, are a clear focus. In the mid-infrared the emphasis is on spectroscopic line imaging surveys rather than in the continuum. The time domain, capitalising on the opportunity for high-cadence measurements, in stable conditions with high photometric precision, also providing a clear Antarctic advantage.

Telescopes in Antarctica do not need to be built for a single purpose. Some experiments require the depths of the Antarctic winter, others can be undertaken quite easily in daylight. Consideration should be given to such multi-mode operation, with projects which can be conducted in the summer daylight, in the twilight periods around the equinoxes and in the full Antarctic winter. Different instruments with different design constraints can be built appropriately. The challenge, of course, gets progressively harder as the winter sets in. Summer experiments can be readily set up and operated with people present. Winter experiments may require robotic operation, akin to space-based telescopes, with minimal access possible.

Antarctica does provide the best sites on the surface of our planet for the ultimate Earth-based telescope in the optical and infrared. The route to such a behemoth lies through an intermediate-sized facility – the 2m-class telescope discussed here – where the operational modes can be proven and the engineering challenges identified and solved.

Along the way it will also be able to undertake some excellent science.

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References

Ashley, M.C.B., Burton, M.G., Storey, J.W.V., Lloyd, J.P., Bally, J, Briggs, J.W., Harper, D.A. (1996) South Pole observations of the near-infrared sky brightness. *Publications Astronomical Society Pacific,* **108**, 721-723.

Bayly, P.G.W., Stillwell, F.L. (1923) The Adelie Land meteorite. *Scientific Reports Australasian Antarctic Expedition (1911-1914)*, Series A, **4**, 1, Geology.

Burton, M.G., 2010. Astronomy in Antarctica. *Astronomy and Astrophysics Review*, 18, 417-469.

Burton, M.G., et al. (20 authors) (1994). The scientific potential for astronomy from the Antarctic plateau. *Publications Astronomical Society Australia*, **11**, 127-150.

Burton, M.G., et al. (27 authors) (2005) Science programs for a 2-m class telescope at Dome C, Antarctica: PILOT, the Pathfinder for an International Large Optical Telescope. *Publications Astronomical Society Australia*, **22**, 199-235.

Burton, M.G., Ashley, MC.B., Marks, R.D., Schinckel AE., Storey, J.W.V., Fowler, A., Merrill, M., Sharp, N., Gatley, I., Harper, D.A., Loewenstein, R.F., Mrozek F., Jackson J.M., Kraemer, K.E. (2000) High resolution imaging of photodissociation regions in NGC 6334. *The Astrophysical Journal,* **542**, 359-366.

Burton, M.G., Ashley, M.C.B. (2001) Science goals for Antarctic infrared telescopes. *Publications Astronomical Society Australia*, **18**, 158-165.

Burton, M.G., Burgarella, D., Andersen, M., Busso, M., Eiroa, C., Epchtein, N., Maillard, J-P., Persi, P. (ARENA Working Group 1) (2010) A wide-field, optical/infrared, 2.5m class telescope for Antarctica. *European Astronomical Soc. pub. ser.* **40**, 125-135.

Carlstrom, J.E. et al. (44 authors) (2011) The 10 meter South Pole Telescope. *Publications Astronomical Society Pacific,* **123**, 568-581.

Dopita, M.A., Holland, C.F., Bally, J. Bely, P. (1996) POST: A Polar Stratospheric Telescope for the Antarctic. *Pub. Astron. Soc. Aust.*, **13**, 48-59.

Epchtein, N. (ed.) for the ARENA consortium (2010) A vision for European astronomy and astrophysics at the Antarctic station Concordia, Dome C. Prepared by Antarctic Research, a European Network for Astrophysics (ARENA) for EC-FP6 contract RICA 026150.

Fowler, A. et al. (11 authors). 1998. Abu/SPIREX: South Pole thermal IR experiment. *SPIE*, **3354**, 1170-1178.

Gillingham, P.R. (1993) Super-seeing from the Australian Antarctic Territory. *Australia National Antarctic Research Expedition (ANARE) Research Notes*, **88**, 290-292.

Harper, D.A. (1990) Infrared astronomy in Antarctica. In Pomerantz, M (ed) Astrophysics in Antarctica. *American Institute Physics conf. series*, **198**, 123-129.

Hereld, M. (1994). SPIREX: near infrared astronomy from the South Pole. In McLean IS (ed.) Infrared astronomy with arrays, the next generation. *Astrophysics and Space Science Library*, 190, 248-252.

Indermuehle, B.T., Burton, M.G., Maddison, S. (2005) The history of Astrophysics in Antarctica. *Publications of the Astronomical Society of Australia*, **22**, 73-90.

Lawrence, J.S., Ashley, MCB, Storey, J.W.V. (2005) A remote, autonomous laboratory for Antarctica with hybrid power generation. *Australian Journal Electrical, Electronic Engineering*, **2**, 1-12.

Lawrence, J.S., Ashley, M.C.B., Hengst, S., Luong-Van D.M., Storey, J.W.V., Yang, H., Zhou, X., Zhu, Z. (2009) The PLATO Dome A site testing observatory: power generation and control systems. *Review of Scientific Instruments*, **80**, 064501:1-10.

Lawrence, J.S., Ashley, M.CB, Tokovinin, A., Travouillon, T. (2004) Exceptional astronomical seeing conditions above Dome C in Antarctica. *Nature*, **431**, 278-281.

Lawrence, J.S. et al. (43 authors) (2009a) The science case for PILOT I: summary and overview. *Publications Astronomical Society Australia*, **26**, 379-396.

Lawrence, J.S. et al. (13 authors) (2009b) The science case for PILOT II: the distant universe. *Publications Astronomical Society Australia*, 26, 397-414.

Lawrence, J.S. et al. (23 authors) (2009c) The science case for PILOT III: the nearby universe, *Publications Astronomical Society Australia*, **26**, 415-438.

Maercker, M., Burton, M.G. (2005) L–band (3.5μm) IR-excess in massive star formation. I: 30 Doradus. *Astronomy, Astrophysics*, **438**, 663-673.

Mould, J. (2011) A next generation deep 2μm survey: reconnoitring the Dark Ages, *Publications Astronomical Society Australia*, 28, 266-270.

Pomerantz, M.A. (1986) Astronomy on Ice. *Publications Astronomical Society Australia*, **26**, 415-438.

Rathborne, J.M., Burton, M.G. (2005) Results from the South Pole Infra-Red EXplorer Telescope (SPIREX). *International Astronomical Union Highlights of Astronomy*, **13**, 937-944.

Saunders, W., Gillingham, P., McGrath, A., Haynes, R., Brzeski, J., Storey, J., Lawrence, J. (2008) PILOT: a wide-field telescope for the Antarctic plateau. *Proceedings SPIE* 7012:70124F:1-9.

Severson, S. (2000) Death of a comet: SPIREX observations of the collision of SL9 with Jupiter. *PhD Dissertation*, University of Chicago.

Storey, J.W.V., Ashley, M.C.B, Burton, M.G. (1996) An automated astrophysical observatory for Antarctica. *Publications Astronomical Society Australia*, **13**, 35-38.

Townes, G.H., Melnick G. (1990) Atmospheric transmission in the far-infrared at the South Pole and astronomical applications. *Publications Astronomical Society Pacific*, **102**, 357-367.

Yang, H. et al. (15 authors) (2010) Exceptional terahertz transparency and stability above Dome A, Antarctica. *Publications Astronomical Society Pacific*, **122**, 490-494.

Yuan, X. et al. (14 authors) (2010) Progress of Antarctic Schmidt Telescopes (AST3) for Dome A. *SPIE,* **7733**, 77331V.

Zhao, G.B., Zhan, H., Wang L., Fan Z., Zhang, X. (2011) Probing dark energy with the Kunlun Dark Universe Survey Telescope (KDUST). *Publications Astronomical Society Pacific*, **123**, 725-734.

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Systemic targeted alpha radiotherapy for cancer

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Abstract

The fundamental principles of internal targeted alpha-therapy for cancer were established many decades ago. The high linear energy transfer (LET) of alpha radiation to the targeted cancer cells causes double strand breaks in DNA. At the same time, the short range radiation spares adjacent normal tissues. This targeted approach complements conventional external beam radiotherapy and chemotherapy. Such therapies fail on several fronts, such as lack of control of some primary cancers (e.g., *glioblastoma multiforme*) and inhibition of the development of lethal metastatic cancer after successful treatment of the primary cancer.

This review describes the developing role of systemic high LET, internal radiation therapy. Targeted alpha-therapy (TAT) is a rapidly advancing experimental therapy that holds promise to deliver high cytotoxicity to targeted cancer cells. Initially thought to be indicated for leukaemia and micrometastases, there is now evidence that solid tumours can also be regressed.

Alpha therapy may be molecular or physiological in its targeting. Alpha emitting radioisotopes such as ^{212}Bi, ^{213}Bi, ^{211}At and ^{225}Ac are used to label monoclonal antibodies or proteins that target specific cancer cells. Alternatively, ^{233}Ra is used for palliative therapy of breast and prostate cancers because of its bone-seeking properties.

Preclinical studies and clinical trials of alpha-therapy are discussed for leukaemia, lymphoma, melanoma, *glioblastoma multiforme,* bone metastases, ovarian cancer and pancreatic cancers.

Introduction

This review covers the development of internal, high linear energy transfer (LET) radiotherapy from an Australian perspective – more compete bibliographies are available elsewhere (Elgqvist, 2011). Targeted alpha-therapy for cancer has progressed from early *in vitro* studies, through *in vivo* experiments to Phase 1 and Phase 2 clinical trials.

Our initial studies related to the production and testing of the alpha-emitting radioisotope ^{149}Tb. Other research groups used the accelerator produced ^{211}At. However, the ^{225}Ac–^{213}Bi generator has become the workhorse for the ongoing research.

Targeted Alpha Therapy (TAT) incorporates the essential elements of immunotherapy of cancer: a targeting molecule that fixes to membrane bound molecules on the surface of cancer cells; and a radioisotope label that emits toxic alpha radiation that deposits a large fraction of energy into the targeted cell. There has been a steady rate of *in vitro* and *in vivo* alpha publications over the last 25 years, that have clearly demonstrated the potential superiority of this therapeutic approach. One paper that stands out was the *in vivo* mouse study (Bloomer, 1984) for mice with peritoneal ascites, which showed that while alpha radiation could lead to regression of the ascites, beta radiation could not. This and other papers were the foundations for our extensive alpha research program, which first began with ^{149}Tb, the only lanthanide with a significant alpha-decay branching ratio (Allen, 1996). At the same time, Memorial Sloan Kettering Cancer Center was already well down the track with the Ac:Bi generator, which has transformed the practicality of TAT. ^{152}Tb was later produced at the ISOLDE facility at CERN and ^{149}Tb at the Tandem accelerator at ANU (Allen 2000) and later in clinical quantities at the 1GeV CERN accelerator (Beyer, 2002). However, ^{149}Tb failed the practicality test for clinical applications, i.e., it could not be made readily available for clinical use.

The use of gamma-emitting radioisotopes for imaging is well established in Nuclear Medicine. Radioisotopes such as ^{131}I, ^{123}I, ^{69}Ga, ^{205}Tl and especially ^{99m}Tc are used to label targeting vectors to allow the pharmacokinetics of radio-conjugates to be determined in human patients via single photon emission computer tomography (SPECT). Positron emission tomography (PET) is developing rapidly as an important diagnostic tool, with ^{18}F-labelled fluodeoxyglucose (FDG) being the main workhorse with PET imaging machines. While most Nuclear Medicine procedures relate to imaging, a small proportion use ^{131}I, ^{176}Lu and ^{90}Y for therapy of cancer. However, the therapeutic efficacy of beta emitting radioisotopes has been found to be limited and applications are more successful in the palliative setting. In recent years, alpha-emitting radioisotopes have been used in Phase 1 and 2 clinical trials for various cancers. Results generally indicate substantial efficacy well below or at the maximum tolerance dose. It is these studies that are reviewed here.

A number of symposia on alpha-emitting radionuclides in therapy have been held, the most recent being at Berlin (TAT, 2011). The principles and practices of targeted alpha-therapy (TAT) have been previously reported (eg, Allen, (1999), (2006)). The detailed development of the Bismuth alpha-emitting radioisotopes for therapy has been reviewed by Hassfjell (2001). The most recent and complete report of TAT has been published in special issues of *Current Pharmaceuticals* (Elgqvist (2011)).

In vitro and *in vivo* studies

The Australian program was based on the alpha-emitting radioisotope ^{213}Bi, which is eluted from the ^{225}Ac generator (Finn (1997)). The short half-life of ^{213}Bi, being 46 min, precludes consideration of long biological life times. Monoclonal antibodies have been raised against membrane expressed antigens for many cancers and provide the ability to selectively target those cancers. Stable alpha-conjugates were synthesised in our laboratory by chelating monoclonal antibodies with ^{213}Bi to form the alpha immuno-conjugates (AIC). These were tested *in vitro* and *in vivo* for melanoma (Allen (2001b), Rizvi (2000), leukaemia (Rizvi (2002), colorectal (Rizvi (2001), prostate (Li (2004a, b)), ovarian (Song (2006)) and pancreatic cancers (Qu (2005a, b)).

The short range of alpha-particles, and the short half-life of useful alpha-emitting radioisotopes argue against TAT being at all effective in regressing tumours (Allen (1999a)). Consequently, our studies related to the killing of isolated cancer cells and cell clusters and the inhibition of tumour growth.

To this end we developed the 2-day model, where treatment followed two days post-inoculation of cancer cells.

Mice were then followed until tumours reached ~1 cm^3. In all cases, complete inhibition of tumour development was achieved with 300 μCi local sc injection (i.e., in the same location as the cell inoculation). Higher activities were required for systemic (tail vein or intraperitoneal) injection of the AIC. However, efficacy decreases for longer growth times and larger tumours, but can be partially offset by multiple dosing.

Intralesional alpha-therapy was performed on human melanoma xenografts in nude mice (Allen, 2001b) and showed complete tumour regression over 4-8 weeks. Intralesional TAT of melanoma with 300 mCi gave complete regression of melanoma xenografts in nude mice, but was far less successful in breast and prostate tumours. These results paved the way for the intralesional Phase 1 clinical trial (Allen(2006)), wherein the mouse host for the human melanoma was simply exchanged for a human host.

Acute activity tolerances are in the region of 24-36 mCi/kg for systemic (ip) injections. However, long term toxicity (~6 months in mice) in the form of delayed radiation nephrosis, reduces the MTD to ~9 mCi/kg in mice and between 3 and 9 mCi/kg in rabbits.

While kinetics and bio-distributions will depend on the type of vector used, the melanoma trial provided the basic data to determine specific organ doses for comparison with threshold dose levels and the probability of induced secondary cancer. These data are of considerable value in ensuring patient safety in further systemic Phase 1 clinical trials.

PAI2 – uPAR alpha-therapy

The PAI-2-uPAR targeting system has several important advantages. First, PAI2 is a human protein, rather than a murine antibody, so overcoming problems of immune response. Second, it is a much smaller targeting molecule so can penetrate tissue more efficiently leading to faster targeting, which is important considering the short half-life of the alpha conjugate (46 mins). Finally, pre-clinical studies of over-expression show that uPA is highly expressed in around 75% of pancreatic adenocarcinomas, using immunohistochemical staining, while expression of uPA mRNA in normal pancreas is only 6% of that for pancreatic adenocarcinoma (Nielson (2005); Xue (2008); Qu (2005)). Thus, although there is frequently a high production of uPAR, which predicts poor survival, when there this is countered by a high production of its inhibitor PAI-2 which improved survival results. Therefore the provision of exogenous PAI-2 would not be expected to adversely effect survival.

The human recombinant PAI-2 protein was successfully tested in breast (Allen (2003)), ovarian (Qu (2005), Song (2006, 8), prostate (Li (2002)) and pancreatic (Qu (2005a)) cancers. These conjugates are highly selective of and cytotoxic to targeted cancer cells. In vitro cytotoxicity of alpha-conjugates is very much greater than beta conjugates, non-specific alpha-conjugates and free alpha isotope. The lethal pathway for alpha-therapy is predominantly apoptosis (Li (2004a)).

Preclinical studies of human pancreatic xenografts in nude mice demonstrate complete inhibition of tumour growth at 4 mCi/kg dose at 2 days post-inoculation for local s.c. administration and 9 mCi/kg dose for systemic administration (Qu (2005)). All treated groups showed responses varying from almost complete inhibition to delayed tumour growth compared with controls. However, the low MW of PAI2 means that renal filtration will lead to delayed radiation nephrosis (Allen (2011a)).

A clinical trial for stage IV pancreatic cancer patients who have either completed or declined standard systemic therapies would soon show efficacy because of the poor prognosis. Any delay in progression of the disease would be of clear benefit to the patient. Systemic targeted alpha-therapy has the potential to regress pancreatic cancers and to eliminate micrometastases. TAT could therefore be indicated for the control of pancreatic cancer after resection of the primary tumour, with potential to control the progression of the disease by regression of micrometastases.

C595 anti-mucin alpha-therapy

C595 is an IgG3, murine monoclonal antibody raised against the protein core of human urinary epithelial mucin (MUC1) which is frequently upregulated and abnormally glycosylated in a number of common malignancies, including breast, bladder, colon, ovarian, prostate and gastric cancer. Cancer-associated MUC1 is structurally different to normal MUC1 in that the former has shorter and less dense O-glycan chains, which exposes novel regions of the protein core.

The expression of tumour-associated antigen mucin-1 (MUC-1) on breast, prostate, ovarian and pancreatic cancer cell lines, in cell clusters and animal xenografts was detected by indirect immmunostaining. Monoclonal antibodies (MAbs) C595 (test) and A2 (non-specific control) were labelled with ^{213}Bi using the chelator CHX-A" to form the alpha-immunoconjugate (AIC).

Preclinical results show inhibition of tumour growth and regression of cell clusters. Over 90% of primary prostate, pancreatic and ovarian tumours expressed MUC1 while 95% of normal tissues did not (Qu (2004), Li (2004a), Song (2008b), Allen (2011a)). Further, MUC1 expression was found on the surface of cancer cell lines. The lethal pathway in all *in vitro* studies after TAT was found to be predominantly by apoptosis.

Clinical Trials

A great deal of preclinical work paved the way for the advance to clinical trials in recent years. The Sloan Kettering Memorial Cancer Center has led the way, first with the application of ^{213}Bi immunotherapy and later with ^{225}Ac. Other laboratories have concentrated on ^{212}Bi and ^{211}At. The advantages of the Bi radioisotopes are that they can be generated from long lived parents, ^{225}Ac with 10 d and Th-228 with 1.91 y half-lives, which can be imported from overseas. The Ac-Bi generator has an additional advantage in that it decays in house and does not need long term waste disposal. ^{211}At, with a 7 hr half-life, needs to be used at or near the production site.

While the half-lives of ^{213}Bi (46 minutes) and ^{212}Bi (61 minutes) are rather short, there is sufficient time for synthesis of the alpha-immuno-conjugates, and for vascular distribution throughout the body. However, there is inadequate time for infusion into tumours, which can take 24-48 hours. This is one reason for the development of the ^{225}Ac alpha-conjugate, as the 10 day half-life allows plenty of time for infusion through the target tumours. On the other hand, the short range of the alpha products requires a high degree of homogeneity if all tumour cells are to be neutralised.

Targeting vectors must be specific for the cancers to be treated. As such, a number of vectors are being used or are to be introduced into the clinic. The following monoclonal antibodies (MAb) are in use: humanised HuM195 targets acute myeloid leukaemia (AML); the murine 9.2.27 targets the MCSP antigen on melanoma cells and GBM cells; the anti-CD20 for lymphoma; MX35 F(ab')$_2$ for ovarian cancer; and the human-mouse chimeric anti-tenascin 81C6 for GBM. In the case of bone cancer, $RaCl_2$ has a natural affinity for bone. Other proposed vectors are PAI2 against uPA, which is widely expressed by many cancers at their most malignant stage and C595 a murine MAb against MUC-1, also of generic nature. The polysaccharide capsule binding MAb 18 B7 is proposed for fungal infection.

Seven clinical trials were reported the Berlin TAT symposium (TAT, 2011). ^{213}Bi was used for studies in acute myelogenous leukaemia (AML), melanoma and lymphoma; ^{225}Ac for AML; ^{223}Ra for bone cancer and ^{211}At for the highest grade brain tumour *Glioblastoma Multiforme* (GBM) and ovarian cancer. The Phase 1 ^{213}Bi trial for acute myeloid leukaemia (AML) has been completed and the current trial is Phase 2 with chemotherapy pre-treatment. The intralesional melanoma trial with ^{213}Bi has also been completed, being followed by a systemic trial with the same alpha conjugate. The following sections review the results of past and current clinical trials, and the objectives of proposed trials.

Current and completed clinical trials are as follows:

- Completed Phase I study for AML (Jurcic (2002))
- Ongoing phase II study for post-chemotherapy of AML (Jurcic (2011))
- Ongoing phase I study with ^{225}Ac (Jurcic (2011))
- Completed Phase 1 trial for intralesional melanoma (Allen, (2006))
- Phase 1 trial of systemic melanoma (Raja (2007); Allen (2008), (2011b)),
- Completed Phase 1 trial of GBM (Zalutsky (2005))
- Competed pilot trial of GBM (Cordier (2010))
- Completed trial of ^{223}Ra for bone metastases (Nilsson (2005)),
- Phase 1 for lymphoma (Miederer (2003)).
- Phase 1 trial in GEP-NET (Kratochwil (2011)).

While solid tumours have never been envisaged as suitable targets for TAT, in contrast with liquid cancers and micrometastases (Allen, 1999a), stage 4 advanced cancer patients are used in Phase 1 trials for toxicity studies.

The intralesional melanoma trial and our current systemic melanoma trial use the 9.2.29 mab to target the melanoma-associated chondroitin sulfate proteoglycan (MCSP) receptor expressed by lesions of more than 90% of melanoma patients. This antigen is the same as the HMWMAA and thought to be identical with the NG2 murine anitgen. The antibody is covalently coupled to the cDTPA chelator, and labelled with the ^{213}Bi alpha-emitting radioisotope. The objective of these Phase 1 trials with stage 4 melanoma patients was to determine the safety of the AIC, and so far complications of any type or level have not been observed up to 25 mCi. However, unexpected tumour regressions have been observed at quite low doses, such that a new concept was introduced to explain the clinical responses observed after systemic alpha-therapy, called tumour anti-vascular alpha-therapy (TAVAT) (Allen (2007)).

Leaky neogenic capillaries allow extra-vascular diffusion of the AIC to target antigens on contiguous pericytes and cancer cells. Alpha-emission kills the capillary endothelial cells, shutting down the capillaries with subsequent starvation of the tumour.

Acute myeloid leukaemia (AML)

The feasibility, safety and anti-leukaemic activity of the AIC, ^{213}Bi-CHX-A"-HuM195 was demonstrated in stage 4 subjects with AML (Jurcic (2002)). 18 patients with relapsed and refractory acute myelogenous leukaemia or chronic myelmonocytic leukaemia were treated with 10.36 to 37 MBq/kg of AIC. No significant extramedullary cytotoxicity was observed, but all 17 evaluable subjects developed myelsuppression, with 22 day median recovery time. The AIC localised rapidly within 10 minutes and was retained in areas of leukaemic involvement, including the bone marrow, liver, and spleen.

Absorbed dose ratios for these sites compared to normal tissue were 1,000 times greater than for beta-emitting conjugates. 93% of subjects experienced reductions in circulating blasts, and 78% had reductions in bone marrow blasts. This first alpha-therapy trial in humans showed that the approach was safe, feasible and efficacious.

Acute myeloid leukaemia Phase 1 and 2

The Phase 1 study reported in section 3.1 showed that while massive cell kill could be achieved with TAT, the tumour load (~1 kg) was far too high for control to be achieved. A Phase 1/2 trial was implemented that uses partial cyto-reduction with cytarabine (200 mg/m2/day for 5 days) followed by 0.5 to 1.25 mCi/kg of AIC. The maximum tiolerance dose (MTD) was ~1 mCi/kg, the dose limiting toxicity being myelosupression. 6 of 25 subjects (24%) responded at ~1.0 mCi/kg, with 2 complete responses lasting 9 and 12 months, 2 lasting 2 and 5 months and 2 partial responses lasting 4 and 7 months (TAT (2011).

Intralesional metastatic melanoma

The aim was to develop and implement intralesional targeted alpha-therapy (ITAT) for metastatic melanoma, being the first part of a program to establish a new systemic therapy. The benign targeting vector 9.2.27 was labelled with ^{213}Bi to form the alpha-immunoconjugate ^{213}Bi-cDTPA-9.2.27 (AIC), which is highly cytotoxic to targeted melanoma cells (Allen (2001)).

The safety and efficacy of intralesional AIC in patients with metastatic skin melanoma was investigated in 16 melanoma patients, all with melanomas that were positive to the monoclonal antibody 9.2.27 (Allen (2005)). AIC doses from 50 to 450 μCi were injected into lesions of different sizes, causing massive tumour cell death as observed by the presence of tumour debris. The AIC was very effective in delivering a high dose to the tumour while sparing other tissues. There were no significant changes in blood proteins and electrolytes. There was no evidence of a human-antimouse-antibody reaction. Evidence of significant decline in serum marker melanoma-inhibitory-activity protein (MIA) at two weeks post-TAT was observed.

Intralesional TAT for melanoma in human patients was found to be safe and efficacious to 1350 μCi (Allen (2006)). Tumours were resected at 8 weeks post-ITAT, to show massive cell debris in the injected volume, but no effect in untreated tumour or in the antibody only treated tumour in the same patient. Tumour to kidney activity ratios were ~3000. MIA, apoptosis and ki67 proliferation marker tests all indicated that TAT is a promising therapy for the control of inoperable secondary melanoma or primary ocular melanoma. As such, intralesional TAT could find application for uveal melanoma and brain metastases.

Bone metastases from breast and prostate cancers – Phase 1 trial

^{223}Ra is a bone-seeking alpha-emitter with potential for palliating breast and prostate cancer metastatic to the bone. A Phase 1 trial has been reported for 15 hormone refractory prostate cancer patients and 10 breast cancer patients, all with metastatic bone disease (Nilsson (2005)). Activities of 50 to 250 kBq/kg were well tolerated; 2/25 subjects experienced grade 3 leucopenia; there was no grade 2+ thrombocytopenia and no dose limiting toxicity. 10/25 subjects suffered diarrhea. Evidence of efficacy was found with substantial reductions in serum alkaline phosphatase (ALP) and improved pain control, but was not dose dependent.

Bone metastases from prostate cancers – Phase 2 trial

A randomised, double-blind, placebo controlled, multicentre Phase 2 study investigated the effect of multiple doses of ^{223}Ra in subject with symptomatic hormone-refractory prostate cancer (Nilsson (2007). Efficacy endpoints were the reduction in bone-specific ALP concentration and time to occurrence of skeletal-related events (SRE).

Patients due to receive external beam radiotherapy for pain relief were randomly assigned to four-monthly ^{223}Ra injections or saline injections, in parallel with external beam radiotherapy. Subjects were monitored for survival and long term toxicity out to 24 months. Confirmed PSA response was defined as a 50% reduction from baseline; PSA progression a 25% increase from the nadir and 50% increase for those with a confirmed PSA response. 64 patients were recruited into the trial, 33 being assigned to XBRT plus ^{223}Ra. Baseline values for both groups were not significantly different, nor were adverse events. However, the ^{223}Ra group had significant reductions in all five markers, i.e., bone-ALP, total-ALP, PINP, CTX-1 and ICTP. Significant differences were observed with changes in PSA from baseline to four weeks, PSA decreasing by 24% in the ^{223}Ra group and increasing by 45% in the placebo group. Median time to progression of PSA and survival was 26 weeks and 65 weeks for ^{223}Ra, compared with eight weeks and 46 weeks for placebo (P=0.04 and 0.07).

^{223}Ra was fast-tracked by the US Federal Drug Administration (FDA) and is now the first alpha-therapy to be approved for clinical application, specifically for palliation of bone metastases from prostate cancer.

Glioblastoma Multiforme (GBM)

The first clinical application of ^{211}At in humans involved the injection into the resection cavity of escalating doses of ^{211}At-human antimouse chimeric anti-tenascin MAb 81C6. (Zalutsky, 2005). Injected activities ranged from 2 to 10 mCi, but the MTD was not reached. However, 6 of 17 subjects experienced grade 2 neurotoxicity at 6 weeks, which fully resolved in all but one case. Radionecrosis was not observed. The median delivered dose was 2800 Gy, giving a median survival for GBM subjects (N=14) of 52 weeks and 116 weeks for anaplastic oligodendroglioma (N=3). These results compare favourably with 36 weeks median survival after diagnosis of GBM for standard therapy. Regional administration of ^{211}At-ch81C6 was found to be feasible, safe and efficacious.

Glioma

Critically located gliomas represent a challenging subgroup of intrinsic brain neoplasms because radical treatment and preservation of neurological function are contrary goals. The successful targeting of gliomas with locally injected ^{90}Y-DOTAGA-substance P was not indicated for critically located tumours, where the mean beta range of 5 mm may seriously damage adjacent brain areas. ^{213}Bi emits alpha radiation with a mean range of 81 μm and may have a more favourable toxicity profile. Five patients with critically located gliomas (WHO grades II–IV) were locally injected with ^{213}Bi-DOTA-substance P in a pilot study (Cordier (2010).

Targeted radio-peptide therapy using ^{213}Bi-DOTA-substance P was found to be feasible and tolerated without additional neurological deficit. No local or systemic toxicity was observed. ^{213}Bi-DOTA-substance P showed high retention at the target site. MR imaging was suggestive of radiation induced necrosis and demarcation of the tumours, which was validated by subsequent resection. This study provided proof of concept that targeted local radiotherapy using ^{213}Bi-DOTA-substance P is feasible and may represent an innovative and effective treatment for critically located gliomas. Primarily non-operable glioma may become resectable with this treatment, possibly improving prognosis.

Lymphoma

Twelve subjects with relapsed or refractory non-Hodgkins lymphoma (NHL) have been treated so far with 28, 33, 39 and 44 MBq/kg of ^{213}Bi-anti-CD20, without evidence of short term toxicity. Delayed toxicity was experienced by five subjects with myelosuppression and one subject with fever. The dose limiting organ is bone marrow, which received 3.3 to 7.2 mGy/MBq (Schmidt (2004).

Ovarian Cancer

The α-emitter ^{211}At labelled to a monoclonal antibody has proven safe and effective in treating microscopic ovarian cancer in the abdominal cavity of mice. (Andersson (2009). Women in complete clinical remission after second-line chemotherapy for recurrent ovarian carcinoma were enrolled in a phase I study. The aim was to determine the pharmacokinetics for assessing absorbed dose to normal tissues and investigating toxicity.

Nine patients underwent laparoscopy 2-5 days before the therapy; a peritoneal catheter was inserted, and the abdominal cavity was inspected to exclude the presence of macroscopic tumour growth or major adhesions. ^{211}At was labelled to MX35 F(ab')$_2$ using the reagent N-succinimidyl-3-(trimethylstannyl)-benzoate. Patients were infused with ^{211}At-MX35 F(ab')$_2$ (22.4-101 MBq/L) in dialysis solution via the peritoneal catheter. Samples of blood, urine, and peritoneal fluid were collected at 1-48 hours. Hematology, renal and thyroid function were followed for a median of 23 months.

In terms of the initial activity concentration (IC) of the infused solution, the decay-corrected activity concentration decreased with time in the peritoneal fluid to 50% IC at 24 hours, increased in serum to 6% IC at 45 hours, and increased in the thyroid to 127%±63% IC at 20 hours without blocking and less than 20% IC with blocking. No other organ uptakes could be detected. The estimated absorbed dose to the peritoneum was 15.6±1.0 mGy/(MBq/L), to red bone marrow it was 0.14±0.04 mGy/(MBq/L), to the urinary bladder wall it was 0.77 ± 0.19 mGy/(MBq/L), to the unblocked thyroid it was 24.7 ± 11.1 mGy/(MBq/L), and to the blocked thyroid it was 1.4 ± 1.6 mGy/(MBq/L) (mean ± SD). No adverse effects were observed. Intraperitoneal administration of ^{211}At-MX35 F(ab')$_2$ could achieve therapeutic absorbed doses in microscopic tumour clusters without significant toxicity.

Systemic therapy for metastatic melanoma

The aim of this unique Australian study was to assess toxicity and response of systemic alpha-therapy for metastatic melanoma using the alpha-immunoconjugate ^{213}Bi-cDTPA-9.2.27 (Raja (2007)). Tools used to investigate the responses were physical examination; imaging of tumours; pathology comparisons over 12 weeks; glomelular filtration rate (GFR) for renal activity; computed tomography (CT) for tumour responses and changes in tumour marker over 8 weeks. Responses were based on RECIST criteria.

40 patients with stage IV melanoma/ in-transit metastasis were treated with activities of 55-947 MBq. Using RECIST criteria 50% of subjects experienced stable disease and 12% showed partial response. One patient showed near complete response after a 5 mCi intravenous injection of the AIC (20/21 lesions completely disappeared) and was retreated at 12 months because of an excellent response to the initial treatment. Another patient showed response in his tumour on mandible and reduction in lung lesions. 30% of patients experienced progressive disease over 8 weeks, and all subjects eventually progressed and succumbed to the disease.

The tumour marker melanoma inhibitory activity protein (MIA) reduced over 8 weeks in most patients. However, there was a disparity of dose with responders. Toxicity at any level was not observed over the range of administered activities.

The observation of responses without any toxicity indicates that targeted alpha-therapy has the potential to be a safe and effective therapeutic approach for metastatic melanoma. The observation of efficacy at quite low doses showed that this trial, while adequate as a Phase 1, was inadequate to investigate the underlying factors that were contributing to the unexpected efficacy. As such, the trial was terminated in June 2007 without reaching the MTD and a new trial was designed to provide more detailed information.

Improvements to the trial

The earlier trial used the cDTPA chelator to link the antibody and radioisotope, as this was the only commercially available chelator at that time. As delayed radiation nephrosis is the main concern, CHX-A", being more stable, is expected to reduce the renal uptake of free ^{213}Bi and so increase the maximum tolerance dose for the kidneys. Further, commercial production of CHX-A" is now available (Macrocyclics, USA).

The monoclonal antibody 9.2.27 targets the MCSP antigen and if expression is low, antigens can be more readily saturated and blocked by unlabelled antibody, thus limiting tumour regression. One way around this problem is to increase the specific activity (SA) of the AIC. The AIC is usually prepared by minimizing the free radio-isotope in the labeling process. However, our objective is to minimize the unlabelled antibody fraction. This then leads to a higher SA, less blocking of target antigens, and more effective therapy. Further, the higher specific activity will reduce the amount of antibody injected, even at

higher activities, therefore reducing the HAMA effect.
Dose limiting toxicity will be defined in terms of renal function; GFR Grade1 (normalized for age) or Grade 2 serum creatinine. GFR will be measured at 0, 26, 52 and 78 weeks. If there is >25% decline GFR will be repeated in one month for verification. Serum creatinine will be measured at each visit.

A single administration of AIC was given in the first trial, (if needed 2-3 injections on the same day to achieve the required injected activity). With the higher activities, a fractionated dose regime will be more practical, and may give improved efficacy as tumours capillaries may be damaged, resulting in increased permeability for the AIC. Daily fractionation over 4-5 days would not be of concern for immune response (HAMA) as the time period is too short for the generation of an immune response (7-14 days).

Blocks of previous biopsies will be obtained with the consent of the patient to assess the expression of the targeted antigen MCSP. Tumour biopsy may be taken to observe the effect of the therapy. Biological dosimetry will be obtained by observation of radiation damage to peripheral blood lymphocytes (Song (2007a)). Radiation causes the formation of micronuclei in lymphocytes, which can be counted before and after treatment with blood samples.

Unfortunately, this trial was denied site approval at St George Hospital for fiscal reasons and never proceeded.

Discussion

Alpha therapy for acute myeloid leukaemia was very effective in reducing the cancer cell load. When used with prior chemotherapy at the maximum tolerance dose, some important complete and partial responses are observed.

Patient data for Non-Hodgekins Lymphoma are not as encouraging and its not yet clear if responses will be observed at the maximum tolerance dose.

In the case of intralesional TAT, quite low injected activities (<0.5 mCi) can bring about tumour regression. Even with systemic therapy, and contrary to expectations, melanomas have been completely regressed without recurrence with systemic administration of <10 mCi of AIC. There is no evidence of any adverse events up to 25 mCi. The ability to regress solid tumours was unexpected, and is explained by tumour anti-vascular alpha-therapy (TAVAT), as hypothesised by Allen et al (2007). The diffusion of AIC by leaky tumour capillaries into the peri-capillary space allows the antigens of pericytes and contiguous cancer cells to be targeted, from which alpha rays can kill endothelial cells, leading to closure of the capillaries. If enough capillaries are closed down, then the tumour may regress. The variable tumour capillary permeability is expected to be the major determining factor in TAVAT.

Monte Carlo calculations of the microdosimetry (Huang (2011) show that TAVAT is theoretically possible in terms of ^{213}Bi blood concentrations, endovascular diffusion times and the probability of alpha hits and energy deposition to the capillary endothelial cell nucleus.

Intra-cavity administration of the AIC for GBM shows improved survival of 52 weeks without serious adverse events. This approach is promising for improving prognosis of this fatal disease.

Palliative therapy with ^{223}Ra appears promising for breast and prostate cancer metastatic to the bone. When used as therapy adjunctive to external beam radiotherapy, marked reductions in PSA are seen for prostate cancer.

Intraperitoneal administration of the AIC for ovarian cancer may also be effective, and so far has not induced any adverse events.

A number of preclinical studies should lead to new clinical trials. Among these are the use of PAI2 as a targeting vector for pancreatic cancer. Being a small molecule (MW=47 kD), alpha-PAI2 may more easily diffuse through tumour capillary fenestrations to target cancer cells, and set up a TAVAT effect. On the down side is the higher renal uptake arising from the lower MW. PAI2 targets UPA, a generic receptor expressed by many cancers. Also generic in nature is the MUC-1 receptor, targeted by the MAb c595.

Targeted alpha-therapy could also have application for the control of microbial disease and for AIDS. The potential role of alpha-therapy has been explored for fungal disease, the human pathogens *Cryptococcus neoformans* and *Histoplasma capsulatum*, and pneumococcal infection and viral disease (Dadachova, 2006).

Of some concern is the impact of second cancers, arising from point mutations from stochastic radiation damage to chromosomes and incorrect radiation damage repair. The high radiation weighting factor for alpha-particles (Rw=20) could limit the application of TAT to end stage cancers. The mutagenic potential of ^{213}Bi conjugated to a human melanoma antigen-specific antibody (9.2.27) was examined using an *in vivo* transgenic mouse model containing multiple copies of a lacZ target gene in every cell, allowing the quantification and comparison of mutagenesis in different organs (Allen (2009)). The mutant frequency and mutant spectra were analysed for the brain, spleen and kidneys. The brain and spleen did not show significant increases in induced mutation frequencies compared to spontaneous background levels or changes in mutant spectra, these results being independent of the status of the tumour suppressor gene p53. However, elevated mutation frequencies and persistent size change mutations were observed in the kidneys, but were not significant (P=0.05). The effect of p53 status was also evident, as p53 heterozygotes displayed higher mutation frequencies than their wild-type counterparts, suggesting a reduction in the p53 gene may lead to an increased susceptibility to mutagenesis. These effects were time dependent and levels returned to those of the controls at four weeks post-irradiation, albeit with a predominant residue of size mutations. However, these mutations were observed at activities very much higher than those expected for the therapy of human patients. As such, the induction of secondary cancer with the ^{213}Bi-cDTPA-9.2.27 alpha immunoconjugate is not expected to be a significant problem in the clinic.

The objectives in the application of targeted alpha-therapy (TAT) for cancer therapy relate to the elimination of isolated cancer cells, cell clusters and tumours. Requirements for isolated cancer cells are good cellular targeting, high specific activity and very short range to spare normal tissue. The regression of cell clusters in the peri-vascular space requires high capillary permeability and short range cross fire whereas for developed tumours, good bio-availability and anti-capillary activity are essential (Allen (2011c)).

Of the current sources of alpha radiation, the Ac:Bi generator is the most practical, bringing therapy to Nuclear Medicine with the same practicality as the Mo:Tc generator has for imaging.

Conclusions

Alpha therapy is still a work in progress, but great gains are being made in translating from preclinical studies to clinical trials. Ideally suited to leukaemia, alpha-therapy is demonstrating efficacy, but at the maximum olerance dose level.. *Glioblastoma multiforme* results from intra-cavity administration are very promising, with 52 week median survival. However, the promise of targeted alpha-therapy is greatly extended by the development of tumour antivascular alpha-therapy for solid tumours. Metastatic melanoma results show surprising tumour regressions at doses very much below the maximum tolerance dose and if further research is successful, could change the prognosis for end-stage cancers. More studies are needed in the fields of dose normalization, real time microdosimetry and biological dosimetry for deterministic and stochastic effects.

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References

Allen B.J, Blagojevic, N. Alpha and beta emitting radiolanthanides in targeted cancer therapy: the potential role of terbium-149 (1996) *Nucl Med Communications* 1740-47.

Allen, B.J. (1999a). Can alpha-immunotherapy succeed where other systemic modalities have failed? *Nucl Med Communications,* 20, 205-207.

Allen, B.J. (1999b). Targeted alpha-therapy: evidence for efficacy of alpha immunoconjugates in the management of micrometastatic cancer. *Australas Radiology.,* 43, 480-486.

Allen, B.J., Goozee, G., Sarkar, S., Beyer, G., Morel, C., Byrne, A.P. (2000).

Production of terbium-152 by heavy ion reactions and proton induced spallation. *Applied Radiat Isotopes,* 54, 53-8.

Allen, B.J., Rizvi, S.M., Tian, Z. (2001). Preclinical targeted alpha-therapy for subcutaneous melanoma. *Melanoma Res,* **11**, 175-82.

Allen, B.J., Tian, Z., Rizvi, S.M.A., Li, Y., Ranson, M. (2003). Preclinical studies of targeted alpha-therapy for breast cancer using ^{213}Bi-labelled-plasminogen activator inhibitor type 2. *Brit J Cancer,* **88**, 944-50.

Allen, B.J., Raja, C., Rizvi, S., Li, Y., Tsui, W., Zhang, D., Song, E., Qu, C.F., Kearsley, J., Graham, P., Thompson, J. (2004). Targeted alpha-therapy for cancer. *Phys Med Biol,* **49**, 3703-12.

Allen, B.J., Raja, C., Rizvi, S.M.A., Li. Y., Tsui, W., Graham, P., Thompson, J.F., Reisfeld, R.A., Kearsley, J.H., Morgenstern, A., Apostolidis, C. (2005). Intralesional targeted alpha-therapy for metastatic melanoma. *Cancer Biol Therapy,* **4**, 1318-24.

Allen, BJ. (2006) Internal High LET Targeted Radiotherapy for Cancer. *Phys. Med. Biol.* **51**, R327-R341

Allen, B.J., Raja, C, Rizvi, SMA et al. (2006). Intralesional targeted alpha-therapy for metastatic melanoma. . *Cancer Biol Therapy,* **4**, 1318-24.

Allen B.J., Raja, C., Rizvi, S.M.A., Song, E.Y., Graham, P. (2007) Tumour anti-vascular alpha-therapy: a mechanism for the regression of solid tumours in metastatic cancer. *Phys. Med. Biol.* **52** L15-L19

Allen B.J., Raja, C., Rizvi, S.M.A., Graham, P., Kearsley, J.H.. (2008) New Directions for Clinical Trials of Targeted Alpha Therapy for Metastatic Melanoma. *Current Radiopharmaceuticals* **1**, 240-250.

Allen B.J., So, T, Rizvi, S.M.A., Song, E.Y., Fernandez HR, Lutz-Mann L (2009) Mutagenesis induced by targeted alpha-therapy using ^{213}Bi-cDTPa-9.2.27 in *lac Z* transgenic mice. *Cancer Biol Therapy* **8**, 9, 777-781.

Allen B.J., Rizvi, S.M.A., Qu, C.F., Smith, R.(2011a) Targeted alpha-therapy approach to the management of pancreatic cancer. *Cancers:* Special issue "Pancreatic Cancer" 3, 1821-1843

Allen B.J., Singla, AA, Abbas Rizvi, S.M., Graham, P., Bruchertseifer, F., Apostolidis, C., Morgenstern, A. (2011b) Analysis of Patient Survival in a Phase 1 Trial of Systemic Targeted Alpha Therapy for Metastatic Melanoma. *Immmunotherapy* **3**, 9, 1041-1050.

Allen B.J. (2011C) Future Prospects for Targeted Alpha Therapy. *Current Radiopharmaceuticals* **4**, 4, 336-342

Andersson, H., Cederkrantz, E., Bäck, T., Divgi, C., Elgqvist, J., Himmelman, J., Horvath, G., Jacobsson, L., Jensen, H., Lindegren, S., Palm, S., Hultborn, R. (2009). Intraperitoneal alpha-particle radioimmunotherapy of ovarian cancer patients: pharmacokinetics and dosimetry of 211At-MX35 F(ab')2--a phase I study. *J Nuclear Medicine* **50**, 7, s. 1153-60.

Beyer, G.J., Comor, J.J., Dakovic, M., Soloviev, D., Tamburella, C., Hagebo, E., Allen, B.J., Dmitriev, S.N., Zaitseva, N.G., (2002) ISOLDE Collaboration. Production routes of the alpha-emitting ^{149}Tb for medical application. *Radiochim Acta*, **90**, 247-52.

Bloomer, W.D., McLaughlin, W.H., Atcher, R.W., et al. (1984). ^{211}At radiocolloid therapy: further observations and comparison with radiocoloids of ^{32}P, ^{165}Dy, and ^{90}Y. *Int J Radiat Oncol Biol Phys,* **10**, 341-8.

Cordier, D., Forrer, F., Bruchertseifer, F., Morgenstern, A., Apostolidis, C., Good, S., Mullerprand, J., Maecki, H., Reubi, J.C., Merlo, A. (2010) Targeted alpha-radionuclide therapy of functionally critically located gliomas with ^{213}Bi-DOTA-[Thi8, Met(O2)11]-substance P: a pilot trial. *Eur J Nucl Med Mol Imagimg* **37**, 1335-1344

Cozzi, P.J., Wang, J., Delprado, W., Perkins, A.C, Allen B.J., Russell, P.J., Li, Y. (2005) MUC1, MUC2, MUC4, MUC5AC and MUC6 expression in the progression of prostate cancer. *Clin Exp Metastases* **22**; 565-573

Dadachova, E., Patel, M.C., Toussi, S. et al. (2006) Targeted killing of virally-infected cells by radiolabelled antibodies to viral proteins. *PLoS Medicine* **2**, 11, e427.

Elgqvist, J., (ed.) (2011) *Current Radiopharmaceuticals,* **4,** issues 3 and 4.

Finn, R.D., McDevitt, M.R., Scheinberg, D.A. et al. (1997) Refinements and improvements for ^{213}Bi production and use as a targeted therapeutic radiopharmaceutical. *J Labelled Compds Radiopharm* **40**, 293.

Hassfjell, S., Brechbiel, M.W. (2001) The development of the alpha-particle emitting radionuclides ^{212}Bi and ^{213}Bi, and their decay chain related radionuclides, for therapeutic applications. *Chem Rev,* **101**, 2019-36.

Huang, C.Y., Guatelli, S., Oborn, B.M., Allen B.J. (2012) Monte Carlo calculation of the maximum therapeutic gain of Tumor Anti-vascular Alpha Therapy. *Medical Physics,* **39**, 3, 1282-1288

Jurcic, J., Rosenblat, T.L., McDevitt, M.R., Pandit-Taskar, N., Carrasquillo, J., Divgi, C.R., Sqouros, G., Morgenstern, A., Cicic, D., Larson, S.M., Scheinberg, D.A. (2011) Alpha-particle immunotherapy for acute myeloid leukaemia with Bismuth-213 and actinium-225. *7th Symposium on targeted Alpha Therapy,* Berlin July 17-19

Kratochwil, C., Giesel, F.L., Bruchertseifer, F., Apostolidis, C., Mier, W., Morgenstern, A., Haberkorn. U. (2011) Dose escalation study of peptide receptor alpha-therapy with arterially administered ^{213}Bi-DOTATOC in GEP-NET patients refractory to beta-emitters. *Ann. Congress European Assoc. Nuclear Medicine,* Oct 15-19 Birmingham.

Li, Y., Rizvi, S.M.A., Ranson, M., Allen, B.J. (2002). ^{213}Bi-PAI2 conjugate selectively induces apoptosis in PC3 metastatic prostate cancer cell line and shows anti-cancer activity in a xenograft animal model. *Brit J Cancer,* **86**, 1197-203

Li, Y, Rizvi, S.M.A., Brown, J, Cozzi PJ, Qu, C.F., Ow KT, Tam PN, Perkins, A.C, Russell PJ, Allen B.J. (2004a) Antigenic expression of human prostate cancer cell lines and primary prostate cancer sections for *in vitro* multiple targeted alpha-therapy with ^{213}Bi conjugates. *Int J Radiat Oncol Biol Phys*: **60**, 3, 896-908

Li, Y., Cozzi, P.J., Qu, C.F., Zhang, D.Y., Abbas Rizvi, S.M., Raja, C., Allen, B.J. (2004b). Cytotoxicity of human prostate cancer cell lines *in vitro* and induction of apoptosis using ^{213}Bi-Herceptin alpha-conjugate. *Cancer Letters,* **205**, 161-71.

Miederer, M., Seidl, C, Beyer, G.J, Charlton, D.E., Vrasjes-Duric, S., Comor, J.J., Huber, R, . Nikula, T., Apostolidis, C., Schumacher, C., Becker, K.F., Senekowitsch-Schmidtke, R. (2003). Comparison of the radiotoxicity of two alpha-particle-emitting immunoconjugates, Terbium-149 and Bismuth-213, directed against a tumour-specific, exon 9 deleted (d9) E-cadherin adhesion protein. *Radiat Res,* **159**, 612-20.

Nielsen, A., Scarlett, C.J., Samra, J.S., Gill, A., Li, Y., Allen, B.J., Smith, R.C.(2005) Significant over-expression of urokinase-type plasminogen activator (uPA) in pancreatic adenocarcinoma using real-time quantitative RT-PCR. *J Gastroenterology Hepathology*, **20**, 2, 256-63.

Nilsson, S., Larsen, R.H, Fosså, S D, Balteskard, L., Borch, K.W., Westlin, J.E., Salberg, G., Bruland, O.S. (2005). First Clinical Experience with alpha-Emitting Radium-223 in the Treatment of Skeletal Metastases. *Clin Cancer Res,* **11**, 4451-59.

Nilsson, S., Tranzen, L., Parker, C. et al (2007). Bone-targeted radium-233 in symptomatic, hormone refractory prostate cancer: a randomised, multicentre, placebo-controlled phase II study. *Lancet Oncol,* **8**; 587-594.

Qu, C.F, Li, Y, Song, E, Rizvi, S.M.A., Zhang, D., Samra, J., Smith, R., Perkins, A.C, Apostolidis, C., Allen B.J. (2004) MUC1 expression in primary and metastatic pancreatic cancer cells for *in vitro* treatment by ^{213}Bi-C595 radioimmunoconjugate. *Brit J Cancer* **91**; 2086-2093

Qu, C.F., Song, E.Y., Li Y, Rizvi, S.M.A., Raja, C., Smith R, Morgenstern, A., Apostolidis, C., Allen B.J. (2005a) Preclinical study of ^{213}Bi-labelled PAI2 for the control of micrometastatic pancreatic cancer. *Clin Exp Metastasis* **22**; 575-586

Qu, C.F., Song, E.Y., Li, Y., Rizvi, S.M., Raja, C., Smith, R., Morgenstern, A., Apostolidis, C., Allen, B.J. (2005b) Pre-clinical Study of ^{213}Bi Labeled PAI2 for the Control of Micrometastatic Pancreatic Cancer. *Clin Exp Metastasis,* **22**, 575-86.

Raja, C., Graham, P., Rizvi, S.M.A., Song, E., Goldsmith, H., Thompson, J., Bosserhoff, A., Morgenstern, A., Apostolidis, C., Kearsley, J.H., Reisfeld R, Allen B.J. (2007) Interim analysis of toxicity and response in Phase 1 trial of systemic targeted alpha-therapy for metastatic melanoma. *Cancer Biol Therapy,* **6**, 6, 846-52

Rizvi, S.M.A., Sarkar, S., Goozee, G., Allen B.J. (2000) Radioimmunoconjugates for targeted alpha-therapy of malignant melanoma. *Melanoma Res,* **10**; 281-289

Rizvi, S.M.A., Allen, B.J., Tian, Z., Li, Y., Goozee, G., Sarkar, .S. (2001). In vitro and preclinical studies of targeted alpha-therapy for colorectal cancer. *Colorectal Disease,* **3**, 345-353.

Rizvi, S.M.A., Henniker, A.J., Goozee, G., Allen, B.J. (2002). In vitro testing of the leukaemia monoclonal antibody WM-53 labelled with alpha- and beta-emitting radioisotopes. *Leukemia Res,* **26**, 37-43.

Rizvi, S.M.A., Sarkar, S., Goozee, G., Allen, B.J. (2000) Radioimmunoconjugates for targeted alpha-therapy of malignant melanoma. *Melanoma Research,* **10**, 281-9.

Schmidt, D., Neumann, F., Antke, C., et al. (2004). Phase 1 Clinical Study on Alpha-Therapy for Non-Hodgkin Lymphoma. In *4th Alpha-Immunotherapy Symposium* Morgenstern, A., (ed.) ITU: Dusseldorf, Germany, pp 12

Song, Y.J., Qu, C.F., Rizvi, S.M.A., Li, Y, Robertson, G., Raja, C., Morgenstern, A., Apostolidis, C., Perkins, A.C, Allen B.J. (2006) Cytotoxicity of PAI2, C595 and Herceptin Vectors labelled with the Alpha-Emitting Radioisotope Bismuth-213 for Ovarian Cancer

Cell Monolayers and Clusters. *Cancer Letters*, **234**, 2, 176-183.

Song, E.Y., Rizvi, S.M.A., Qu, C.F., Raja, C., Morgenstern, A., Apostolidis, C., Allen B.J. (2007) Pharmacokinetics and toxicity of ^{213}Bi-labelled PAI2 in preclinical targeted alpha-therapy for cancer. *Cancer Biol Therapy*, **6**, 6 898-904.

Song, E.Y., Rizvi, S.M.A., Raja, C., Qu Changfa, Yuen, J., Morgenstern, A., Apostolidis, C., Allen B.J. (2008a) The cytokinesis–block assay as a biological dosimeter for targeted alpha-therapy. *Phys Med Biol.*, **53**, 319-328.

Song, E.Y., Qu, C.F., Rizvi, S.M.A., Raja, C., Beretov, J., Morgenstern, A., Apostolidis, C., Perkins, A., Allen B.J. (2008b) Bismuth-213 radioimmunotherapy with C595 anti–MUC1 monoclonal antibody in an ovarian cancer ascites model. *Cancer Biol Therapy* 7, 76-80

TAT 2011: *7th Symposium on targeted Alpha Therapy*, Berlin, July 17-19.

Xue A, Scarlett C.J., Jackson C.J., Allen B.J., Smith R.C.(2008) Prognostic significance of growth factors and the urokinase-type plasminogen activator system in pancreatic ductal adenocarcinoma. *Pancreas*, **36**, 2, 160-7.

Zalutsky, M.R, Bigner, D.D. (1996). Radioimmunot.herapy with alpha-emitting radioimmunoconjugates. *Acta Oncologia* 35, 373-9

Zalutsky, M.R. (2005). Current status of therapy of solid tumours: brain tumour therapy. *J Nucl Med*, **46**, 151S-156S.

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Watson and Theischinger: the etymology of the dragonfly (*Insecta: Odonata*) names which they published

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Abstract

Tony Watson and Gunther Theischinger have been prolific publishers on the taxonomy of Australian Odonata since the late 1960s. Between them they have named about 12% of the Australian genera and 28% of the species. The etymology of the scientific name of each of their taxa is given as quoted in the original description or deduced.

Keywords: *Odonata*, dragonflies, etymology, Theischinger, Watson

Introduction

At present, the odonate fauna of Australia comprises 325 species in 114 genera, including subgenera (Theischinger and Endersby 2009) and is considered to be well known. The discovery and naming of these species falls approximately into three eras (Table 1). During the first of these, all Australian Odonata were referred to European experts, dominated eventually by Baron Michel Edmond de Sélys Longchamps in the latter half of the 19th century, who described 39 Australian species and 22 of our current genera. The second era was dominated by R.J. Tillyard, an Australian-based World authority who described 87 species and 21 genera. Other contributions during this phase were made by F.C. Fraser and several European taxonomists. The third era, which slightly overlaps the previous one, was dominated by J.A.L. Watson and Gunther Theischinger, whose contributions and collaborations are given in Table 2. Between them they have named about 12% of the Australian genera of Odonata and 28% of the species.

In the nineteenth and early twentieth centuries, when many Australian species of dragonflies were described, original descriptions rarely included an explanation of the etymology. In more recent times that has changed, with the explanation sometimes actually specifying the Latin grammatical status of the new name. Nevertheless not all recent names are easily understood, and it is the aim of this paper to clarify them.

		Genera	Species
1770 -1906	European Era	57	116
1907-1958	Tillyard Era	35	114
1959 – present	Recent Era	22	95
		114	325

Table 1. Description of the Australian species of Odonata

	Genera	Species
Brown & Theischinger		1
Theischinger	4	32
Theischinger & O'Farrell		4
Theischinger & Watson	1	11
Watson	8	32
Watson & Arthington		1
Watson & Moulds		2
Watson &Theischinger		8
	13	91

Table 2. Australian Odonata taxa named by Watson, Theischinger and their associates

John Anthony Linthorne Watson (1935 – 1993) graduated from the University of Western Australia with a scholarship that enabled him to work in the laboratory of Sir Vincent Wigglesworth at Cambridge University. After a period in Cleveland, Ohio he returned to Australia as a Queen Elizabeth II Fellow studying silverfish, and was then appointed to the Division of Entomology, CSIRO to research the biology and taxonomy of termites. Although working officially on termites, his love of dragonflies never waned and he became one of the world's leading odonatologists. He and Günther Theischinger have collaborated extensively.

Günther Theischinger (1940 –) was Curator of Invertebrates at the Oberösterreichisches Landmuseum in Linz prior to coming to Australia. Here he worked for nearly 20 years in private industry before he was given the opportunity of curating all the aquatic insect orders in the Division of Entomology, CSIRO and of working as a taxonomist identifying aquatic macroinvertebrates for Environment Protection Authority/Office of Environment and Heritage. He has published extensively on the taxonomy of Plecoptera, Megaloptera, Tipulidae and Odonata. He is a Research Associate at the Australian Museum and a Visiting Fellow at the Smithsonian Institute.

This paper provides the etymology of each of the genus and species-group names for the taxa described by Watson, Theischinger and their collaborators.

Methods

All original descriptions of the taxa involved were sighted. The following hierarchy is used to analyse each entry:
(1) When the etymology is included it has been directly quoted;
(2) If the etymology is not quoted but the Greek or Latin roots are obvious then a search has been made of the original description for the terms which best match those roots;
(3) If no obvious characters are apparent, the roots are given with some speculation as to how they might apply

Derivations of the genera *Aeshna*, Fab., *Agrion*, Fab., *Argiolestes*, Selys, *Austrogomphus*, Selys, *Austrolestes*, Till. *Cordulia*, Leach, and *Libellula*, Linn. are given also as they form part of the compound names of a number of genera described by the recent authors, or are included in the discussion.

Direct quotations from references are given in single inverted commas. Square brackets are used for translations, clarifications and comments.

The names of genera are, by convention, nouns in the nominative case. The gender of each (masculine, feminine or neuter) is given in {braces} at the end of its entry. The grammatical status of each species name is given in braces at the end of the entry, viz. a noun in apposition; a noun in the genitive case (usually an eponym); a declinable adjective or participle. Theischinger uses the German convention of using the figure 3 associated with a Latin adjective to indicate that three gender endings are available to agree with genus names of different genders, e.g: for first and second declension adjectives – lewisianus 3 = lewisianus (masculine), lewisiana (feminine) lewisianum (neutral). The provision of declensions is significant especially should the species name be at any time transferred to a genus of different gender from the original under ICZN regulations (ICZN 2000). The International Commission on Zoological Nomenclature (ICZN) acts as adviser and arbiter for the zoological community by generating and disseminating information on the correct use of the scientific names of animals. It has responsibility for producing the International Code of Zoological Nomenclature – a set of rules for the naming of animals and the resolution of nomenclatural problems.

The page numbers given with each generic or specific name refer to the page from which the quotation is taken. They do not necessarily come from the original description but could be from the introduction to the paper or its acknowledgements.

Williams (2005) was an excellent source for determining the probable construction of each genus and species name, if it had not been defined by the author. Greek roots were taken from Liddell and Scott (1996). Latin roots were from Collins (2005) The abbreviations Gr. = Greek and L. = Latin.

Etymology of the scientific names

Adversaeschna Watson, 1992: 469, 470

‘*Adversus*, opposite in physical position.’ ‘This comparison between *Aeshna brevistyla* and its congeners confirms its taxonomic isolation, except from *Oreaeschna*.’ + aeschna (q.v.). {Feminine}

Aeshna Fabricius, 1775: 424

Æshna Fabricius, 1775 was published originally without citation of its derivation. Hemming (1958) records that Mr. R. A. Muttkowski had submitted a case for amending the ‘barbaric *Æshna* to. *Æschna*, a *lapsus calami* being assumed’. He argued *inter alia* that *Æshna* is not a Greek spelling and ‘Fabricius being a purist, as is evident from most of his generic names, the elision of ‘c’ in *Æshna* suggests a typographical error’.

In searching for possible derivations Muttkowski quoted αἰσχρός = ugly and αἰσχύνω = disfigured (after death), with a preference for the latter as the former would lead to *Æschrus*. Quoting the submission and other references, The International Commission on Zoological Nomenclature (Hemming 1958) recognised that a certain amount of speculation was required in arriving at the derivation of the name. It declared that it was of the ‘opinion that since the original publication of *Æshna* Fabricius, 1775, 424-425, does not indicate clearly the origin of the word, it is not evident that there is either an error of transcription, a *lapsus calami*, or a typographical error present. It is, therefore, the opinion of the Commission that the original spelling, namely, *Æshna*, should be preserved.’

However, -*aeschna* is retained in compound names such as *Adversaeschna*, *Austroaeschna*, *Notoaeschna*, *Spinaeschna*, and many other extralimital ones also {Feminine}

Agrion Fabricius, 1775: 425

Agrion was the name established by Fabricius (1775) to contain all of the Zygoptera. It is derived from Gr. ἄγριος = living in the fields or “wild”, and Fliedner (2006) suggests this was chosen because the insects live in the fields rather than domestic areas. {Neuter, although Fabricius treated the name as Feminine} *aleison, Austrolestes* Watson & Moulds, 1979: 144

‘αλεισον, a goblet, referring to the goblet-shaped mark on abdominal segment 2 of the male.’ Gr. ἄλεισον. {noun in apposition}

Apocordulia Watson, 1980: 287

‘From the Greek *apo*, from or away, referring to the divergence of these dragonflies from normal corduliid appearance.’ Gr. ἀπό = from or away + *Cordulia* (q.v.). {Feminine}

Argiolestes Selys, 1862: 38

Selys’ intent is not known but, whether by design or default, he has used argio- as an anagram of agrio- itself based on the genus *Agrion* (q.v.). In naming Sous-genre 1 – *Argiocnemis* and Sous-genre 2 – *Agriocnemis*, within Genre 4 – *Argiocnemis*, Selys (1877), provides another example of this construction. Rambur (1842) had previously taken a similar path in naming the North American genus *Argia* with a name signifying its closeness to *Agrion* ‘par le ptérostigma et les deux nervules du premier espace costal elles se rapprochent des *Agrion*’. [in the the pterostigma and two veins of the first costal space they approach *Agrion*.]. In discussing *Argia* Rambur, 1842, Fliedner (2006) dismisses Greek mythology as a source and argues that Rambur looked for a name as similar to *Agrion* as possible without causing confusion. Perhaps Selys took this approach as his model. {Masculine}

atratus, Hemigomphus Watson, 1991a: 316, 315

‘*Atratus*, clothed in black’ referring to ‘Abdomen. Substantially blackish brown to black;’ L. atratus –a –um. {declinable adjective}

aureum, Pseudagrion ignifer Theischinger, 1997a: 802

‘aureus 3 = Latin for “golden”, referring to the pale yellow face of the male.’ L. aureus –a –um. {declinable adjective}

Austrogomphus Selys, 1854

L. auster (stem austro-) = south wind, hence south (meaning Australia) + Gr. γόμφος = peg, bolt or pin, alluding to the shape of the male abdomen in most species, which appears like the bolt used for ship building. {Masculine}

Austrolestes Tillyard, 1913: 410, 421-424

L. auster (stem austro-) = south wind, hence south (meaning Australia) applied to the genus *Lestes* from Gr. ληστής = robber. Tillyard (1913) provides the root (incorrectly spelled) and disputes Selys’ assignation of the female gender. ‘Greek ληστής = a robber or pirate, masculine (rarely used in the common gender). I have therefore treated *Lestes* and its derivations as masculine, though de Selys used feminine terminations with them’. {Masculine} *barbarae, Lestoidea* Watson, 1967a

Although not acknowledged in the original description, this species was obviously named for the author's wife, Barbara. {noun in the genitive case}

baroalba, Nososticta Watson & Theischinger, 1984: 7

'Holotype ♂: Baroalba Creek springs, 19 km NE. by N. of Mt Cahill, Northern Territory' {noun in apposition}

bicolor, Notolibellula Theischinger & Watson, 1977: 417

'In 1968, Watson encountered specimens of a vivid blue and red, broad-bodied libelluline dragonfly in the Kimberley region, in the north of Western Australia.' L. bicolor –or –or. {declinable adjective}

boumiera, Orthetrum Watson & Arthington, 1978: 152

'The specific name is derived from the Aboriginal name for Brown Lake, North Stradbroke Island. It is to be treated as an undeclinable noun.' {noun in apposition}

brevicauda, Lestoidea Theischinger, 1996b: 318

'A combination of the L. brevis (= short) and L. cauda (= tail) refers to the short inferior appendages of the male.' {noun in apposition}

brookhousei, Austroargiolestes Theischinger & O'Farrell, 1986: 409

'The species is dedicated to Mr P. Brookhouse who was much involved in collecting material for this study.' {noun in the genitive case}

bucki, Griseargiolestes Theischinger, 1998e: 623

'Dedication to Dr K. Buck of Wilster, Germany, prolific photographer of Australian dragonflies.' {noun in the genitive case}

christine, Austroaeschna Theischinger, 1993: 806

'After my wife Christine; to be treated as a noun in apposition.' {noun in apposition}

christine, Austroargiolestes Theischinger & O'Farrell, 1986: 394

'The species is named after Mrs Christine Theischinger, *christine* being regarded as a noun in apposition to the generic name.' {noun in apposition}

convergens, Micromidia Theischinger & Watson, 1978: 423

'the superiors … slightly longer than inferior, convergent, with strong ventrobasal tooth in *M. convergens*.' L. convergens –ens –ens.{declinable present participle.}

coolawanyah, Eurysticta Watson, 1969a: 67

Although the type locality is Deep Reach, Fortescue R., Millstream Station, WA, the species is named for Coolawanyah Station, Pilbara, WA. {noun in apposition} *cooloola, Austroaeschna* Theischinger, 1991: 39

First described as a subspecies of *A. unicornis*. Type locality: 'Searys Creek near Rainbow Beach, Cooloola National Park, Queensland.' {noun in apposition}

cooloola, Hemigomphus Watson, 1991a: 321

'From Cooloola National Park, in southern Queensland, the only locality where this species has been found; to be treated as a noun in apposition.' {noun in apposition}

coomalie, Eurysticta Watson, 1991b: 28

'The name refers to the locality from which this insect was first recognised [Coomalie Creek, Northern Territory]; used as a noun in apposition.' {noun in apposition}

Cordulia Leach, 1815: 137

Leach (1815) introduced the genus name *Cordulia*, without explanation. It is the adjectival form of the Gr. κορδύλη = club or cudgel, alluding to the shape of the abdomen in the males of the genus *Cordulia*. {Feminine}

cornutus, Austrogomphus Watson, 1991a: 392

'*Cornutus*, horned, referring to the horn on the male occiput.' L. cornutus –a –um. {declinable adjective}

cristatus, Episynlestes Watson & Moulds, 1977: 258

L. cristatus –a –um = with a crest, plume or comb.

'Superior appendages … each bearing crest of black setae approximately 0.8 mm long, the crests interlocking at their bases.' {declinable adjective}

deniseae, Eusynthemis Theischinger, 1977: 105

'The new species is named after my daughter, Denise.' {noun in the genitive case}

dentosus, Antipodogomphus Watson, 1991a: 349

'Referring to the large, composite tooth on each side of the female occiput.' L. dentosus –a –um having teeth. {declinable adjective}

divaricatus, Austrogomphus Watson, 1991a: 421

'Referring to the divaricate superior appendages of the male, and emphasising the close affinity with *Austrogomphus bifurcatus*.' L. divaricatus –a –um = spread apart. {declinable perfect participle}

dobsoni, Ictinogomphus (Watson, 1969a): 88

'Two subspecies have hitherto been recognized, *I a. australis* and a darker form, *I. a. lieftincki* (Schmidt, 1934), the former occurring in Queensland, the type locality, and the Northern Territory, and the latter in New Guinea, Halmahera, and the Solomons. The specimens from the Hamersley Range are paler than either of these two subspecies, particularly on the abdomen, and may therefore be designated *I. a. dobsoni*, subsp, nov.' R. Dobson is cited as collector of extralimital (Queensland) material. Roderick Dobson collected dragonflies and other aquatic insects in Australia between 1948 and 1958, and made a return visit from his home in Jersey, Channel Islands in 1967-68. {noun in the genitive case}

donnellyi, Odontogomphus Watson, 1991a: 337
'Named for its discoverer, odonatist and geologist T.W. Donnelly.' {noun in the genitive case}

edentulus, *Antipodogomphus* Watson, 1991a: 352
'Lacking teeth, in reference to the unarmed occiput in the female.' [cf. *Antipodogomphus dentosus*] L. edentulus, –a –um = toothless.{declinable adjective}

elke, Austroargiolestes Theischinger & O'Farrell, 1986: 396
'The species is named after Mrs Elke Müller, the wife of one of its collectors, *elke* being regarded as a noun in apposition to the generic name.' {noun in apposition}

eungella, Austroaeschna Theischinger, 1993: 810
'From Eungella, in north-eastern Queensland; to be treated as a noun in apposition.' {noun in apposition}

Eurysticta Watson, 1969a: 83
'The name of the new genus, derived from the Greek ευρυσ [= wide, broad], emphasizes the broadness of the abdomen in both sexes, and the additional swelling of the ninth segment in the female.' Gr. εὐρύς = wide + sticta which is derived from the Gr. adjective στικτός = spotted, tattooed, but, in this case, the root refers to the subfamily Isostictinae Fraser, in which it was placed. {Feminine}

flava, Hemicordulia Theischinger & Watson, 1991: 44
'*flavus*, yellow, refers to the extensive yellow coloration.' L. flavus –a –um. {declinable adjective}

fraseri, Neosticta Watson, 1991b: 36
'Named for the late F.C. Fraser who, in 1960, illustrated this species (as *Neosticta silvarum*).' {noun in the genitive case}

frater, *Austrosticta* Theischinger, 1997b: 807
'Frater = Latin for "brother", a match for soror (= Latin for "sister").' {noun in apposition}

garrisoni, Lathrocordulia Theischinger & Watson, 1991: 48
'Named in honour of its discoverer, Rosser Garrison.' {noun in the genitive case}

geminata, Notoaeschna Theischinger, 1982: 36
'Tillyard (1916) named as 'var. *geminata*' specimens from Guy Fawkes (Ebor), N.S.W., which he thought belonged to *N. sagittata* (Martin). Although Tillyard did not expressly

allocate infrasubspecific status to the variety, there is, as Watson (1969b) has pointed out, no reason to suppose that 'var. *geminata'* is anything more than infrasubspecific. However, as Tillyard's specimens of 'var. *geminata'* are not conspecific with *N. sagittata*, I here use *geminata* as the name of a new species of *Notoaeschna*, based on Tillyard's series from Ebor.'

Tillyard (1916: 59) 'a very fine and long series taken by me at Guy Fawkes, N.S.W., is distinct enough to warrant a varietal name. I therefore propose for it the name var. *geminata* defined by the following characters:- … Sagittate dorsal spots of abdomen much reduced, each being split into two geminate [paired] subtriangular halves separated by the black line of the dorsal ridge.' L. geminatus –a –um = doubled, twinned. {declinable perfect participle}

gordoni, Austroepigomphus (Watson, 1962): 8

Name first made available in a checklist (p. 8) to the Dragonflies of South-western Australia, and in keys to the larvae (p. 13) and adults (p. 20). From Watson (1969a: 90) 'This species, inadvertently named in Watson (1962), is most closely related to *A. turneri* Martin, 1901, from northern Queensland and the Northern Territory. … The specific name commemorates Mr. Stewart Gordon, of a family long associated with Millstream and Kangiangi Stations [Pilbara, WA]' {noun in the genitive case}

Griseargiolestes Theischinger, 1998d: 614

'Combination of grise (from griseus [= grey, pearl-grey]) and *Argiolestes* [q.v.]' referring to the pruinescence attained by the species. {Masculine}

hesperia, Petalura Watson, 1958: 116, 120

'Derived from the Greek ἑσπερος – western' referring to 'This new species, the first recorded from Western Australia.' Gr. adj. ἑσπέριος -ία -ιον = towards evening, hence western. {declinable adjective}

hodgkini, Antipodogomphus Watson, 1969a: 110

'Dr. E.P. Hodgkin, Department of Zoology, University of Western Australia, provided the initial material on which the project was based, and supervised the early stages of the work.' {noun in the genitive case}

ingrid, Austroaeschna Theischinger, 2008: 242

'The species is named for my granddaughter Ingrid, her name being used as a noun in apposition to the generic name.' {noun in apposition}

injibandi, Nannophlebia Watson, 1969a: 100

'The name commemorates the Injibandi tribe, which previously occupied the tableland adjacent to Millstream.' {noun in apposition}

intermedius, *Episynlestes* Theischinger & Watson, 1985: 146
‘As the name implies, *E. intermedius* bridges the gap between *E. albicauda* and *E. cristatus*, it is intermediate in some characters, like *E. albicauda* in some, and like *E. cristatus* in others.’ L. adj. intermedius –a –um = intermediary. {declinable adjective}

isabellae, Austroargiolestes Theischinger & O’Farrell, 1986: 400
‘The species is dedicated to Mrs Isabel O’Farrell.’ {noun in the genitive case}

jedda, Pseudagrion Watson & Theischinger, 1991: 26
‘Named for Jedda in the 1955 film of that name; parts of the film were set in Katherine Gorge. [Type locality – Katherine River, NT]. To be treated as a noun in apposition.’ {noun in apposition}

jurzitzai, Austrocordulia refracta, Theischinger, 1999d: 381
‘Dedication to Professor Gerhard Jurzitza who acted incredibly fast and unselfish when the undescribed larval material of *Gomphomacromia* Brauer was needed for a study of the Australian Gomphomacromiinae (Theischinger & Watson, 1984)’. {noun in the genitive case}

kalliste, *Hemicordulia* Theischinger & Watson, 1991: 46
‘The name commemorates ‘Kalliste’, the home of the late Dr. M.A. Lieftinck and his wife Corrie, in Rhenen, the Netherlands.’ Kalliste, from the Gr. superlative adjective καλλιστη = most pretty. {noun in apposition}

kalumburu, Nososticta Watson & Theischinger, 1984: 14
‘Holotype ♂: … Drysdale River, Western Australia’ Kalumburu and Kalumburu Community (formerly Drysdale River Mission) are both localities within the Shire of Wyndham-East Kimberley. {noun in apposition}

koolpinyah, Nososticta Watson & Theischinger, 1984: 16
‘Holotype ♂: … Black Jungle, Koolpinyah Station, Northern Territory’ {noun in apposition}

koomina, Hemicordulia Watson, 1969a: 97
‘Material. – 2 ♀ (bred from larvae), Koomina Pool, Tanberry Creek [Sherlock River system, Hamersley Range WA]’ {noun in apposition}

koongarra, Nososticta Watson & Theischinger, 1984: 20
‘Paratypes 15 ♂, 7 ♀, Koongarra … 15 km E. of Mt Cahill, [NT]’ plus three other collections from the same locality. {noun in apposition}

kunjina , *Agriocnemis* Watson, 1969a: 76
‘Material. … 1 ♀, Kunjina Spring, Daniel’s Well [Station]’. Fortescue River System, Hamersley Range, WA. {noun in apposition}

kununurra, Eurysticta Watson, 1991b: 31

Type locality: Ord River and Packsaddle Plains, Kununurra, Western Australia. 'The name is to be used as a noun in apposition.' {noun in apposition}

Labidiosticta Watson, 1991b: 22

'Name derived from the Greek *labidion*, small tongs, referring to the shape of the male superior appendages.' Gr. λαβίδιον = pair of tweezers + -sticta which is derived from the Gr. adjective στικτός = spotted, tattooed , but, in this case, the root refers to the second phrase of the genus *Phasmosticta*, in which *L. vallisi* was originally included, rather than necessarily being a character of the species itself. {Feminine}

leonardi, Austrocordulia Theischinger, 1973: 388

'Ich möchte meinem Freund, Herrn Leonard Müller, der viele Tage mit mir auf Exkursionen in Australien verbrachte, für seine wertvolle Hilfe danken.'
[I want to thank my friend, Mr. Leonard Mueller, who spent many days with me on trips in Australia, for his valuable help.] {noun in the genitive case}

lewisiana, Lestoidea Theischinger, 1996b: 320

'Lewisianus 3 = Latinized for "from Mount Lewis"' L. lewisianus –a –um {declinable adjective}

Libellula Linnaeus, 1758: 543

Linnaeus erected *Libellula* for all known Odonata. Two derivations have been postulated (1) the diminutive of the Latin libella, a carpenter's level which was T-shaped or (2) from the Latin libellus, the diminutive of liber, meaning a little book, perhaps as a reference to wings folding like pages of a book, but this alternative has little support.

Corbet 1999: 561-562 discusses the alternatives at length and concludes that 'the resemblance of the zygopteran larva to a T-shaped balance, as typified by the hammerhead shark [*Libella marina* Rondelet], is responsible for the generic name *Libellula*.' Tillyard (1917), without citing references, reports that Littré guesses *libellus* (petit livre) while Professor MacCallum prefers 'a diminutive of *libella* (a balance) on account of the way that these insects poise their wings in flight or at rest.' Fraser (1950) champions the Rondelet analogy while Fliedner (1997) dismisses the derivation of *libellus* as being linguistically incorrect. 'Die Ableitung des Wortes libéllula von *libellus* (= Büchlein; Diminutive zu liber = Buch) ist nicht möglich, da dieses Wort maskulin ist und nur eine Verkleinerung *libellulus* (= Büchelchen) hervorbringen könnte.' [To derive the word libellula from *libellus* (= booklet; diminutive of liber = book) is not possible, as this word is of masculine gender and its diminutive only could be *libellulus* (= little booklet)]. {Feminine}

Lithosticta Watson, 1991b: 22

'Name derived from the Greek *lithos*, alluding to the stony habitats from which these damselflies have been recorded.' Gr. λίθος = stone + -sticta which is derived from the Gr. στικτός = spotted, tattooed , but, in this case, the root refers to the second phrase of the family Isostictidae rather than necessarily being a character of the species *L. macra* itself. {Feminine}

litorea, *Petalura* Theischinger, 1999a: 160
'Litoreus 3 = Latin for "belonging to the shore"'. L. litoreus –a –um. {declinable adjective}

liveringa, Nososticta Watson & Theischinger, 1984: 23
'Paratypes: Western Australia: ... 8 ♂, 9 ♀, Camballin, Fitzroy River barrage dam …' Most probably the locality Lower Liveringa Pool, Camballin WA, Australia. {noun in apposition}

longipositor, Zephyrogomphus (Watson, 1991a): 341
'Referring to the extraordinarily long ovipositor.' {noun in apposition}

lucifer, Pseudagrion Theischinger, 1997a: 803
'lucifer = Latin for "morning-star", referring to the bright face of the male.' {noun in apposition.}

macra, Lithosticta Watson, 1991b: 34
'Name derived from the Latin *macer*, lean.' Feminine form of the L. adj, macer, macra, macrum. {declinable adjective}

macrops, Apocordulia Watson, 1980: 287
'From the Greek *makros*, long, and *ops*, eye, referring to the long eye seam; a noun in apposition.' Gr. μακρός = long + Gr. ὤψ = eye. {noun in apposition}

magela, Hemigomphus Watson, 1991a: 324
'From Magela Creek, in western Arnhem Land; to be treated as a noun in apposition.' {noun in apposition}

magnifica, Archaeophya Theischinger & Watson, 1978
L. magnificus –a –um = great, splendid. There is nothing in the original description to indicate which aspects of this species warrant the epithet 'magnificent'. Both species in the genus are large and metallic black with yellow markings. {declinable adjective}

melvillensis, Huonia Brown & Theischinger, 1998: 99
'a species of *Huonia* was collected as part of a freshwater survey of Melville Island. Since it is different from all described species, it is described as new below.' A derived adjective indicating place of origin. L. melvillensis –is –e. {declinable adjective}

Miniargiolestes Theischinger, 1998d: 615
'Combination of mini (from minimus) and *Argiolestes* [q.v.].' {Masculine}

minjerriba, Austrolestes Watson, 1979: 147

'*minjerriba*, the Aboriginal name for North Stradbroke Island, where the species was first discovered; to be treated as an undeclinable noun.' {noun in apposition}

mouldsi, Nososticta Theischinger, 2000: 1175

'Dedication to Dr M.S. Moulds.' {noun in the genitive case}

mouldsorum, Austrogomphus Theischinger, 1999b: 369

'Dedication to the collectors M.S. and B.J. Moulds.' {noun in the genitive case plural}

mudginberri, Nannophlebia Watson & Theischinger, 1991: 49

'Named after Mudginberri Station [Northern Territory, 12º 35' 49", 132º 52' 20"]; name to be treated as an undeclinable noun.' {noun in apposition}

muelleri, Austroaeschna Theischinger, 1982: 45

'I also wish to express my special gratitude to my friends Mr L Müller (Berowa) and Dr J.A.L. Watson (Canberra) who supported my work in many ways.' {noun in the genitive case}

netta, Eusynthemis Theischinger, 1999c: 374

'Dedication to Mrs N. Smith, cocollector of this species.' {noun in apposition}

Notolibellula Theischinger & Watson, 1977: 417

'With the characters of the subfamily Libellulinae (*sensu* Fraser 1957).' and 'Subsequent investigations have shown not only that the species is undescribed, but also that its characteristics do not fit any of the described genera of Libellulinae (sensu Fraser 1957)'. When naming *Notoaeschna* Tillyard, (1916: 58) advised 'Greek Νότος, the South Wind. The prefixed *Noto*- and *Austro*- may conveniently be used to denote purely Australian genera.' *Notolibellula* uses the same construction, viz., νότος + *Libellula* (q.v.) to recognise its southern/Australian distribution as opposed to *Libellula* which is predominantly a European genus. {Feminine}

nourlangie, Gynacantha Theischinger & Watson, 1991: 41

Named for Nourlangie Creek, West Arnhem Land, Northern Territory. 'Name to be treated as an undeclinable noun.' {noun in apposition}

obiri, Indolestes Watson, 1979: 152

'*obiri*, for Obiri (Oberie) Rock, a habitat of this cave-haunting lestid; to be treated as an undeclinable noun.' {noun in apposition}

obscura, Austroaeschna Theischinger, 1982

'I named *A. obscura* so because it is markedly darker than *A. multipunctata*, with the pale anterodorsal spots in mature adults usually no longer present from segment 4 or at least 5' (G. Theischinger, in litt. November 2011). L. obscurus –a –um = obscured, dark. {declinable adjective} *obscura, Austrocnemis* Theischinger & Watson, 1991: 24

'The name alludes to the obscure coloration of this species, in contrast to its more brightly coloured congener, *A. splendida*.' L. obscurus –a –um = obscured, dark. {declinable adjective}

Odontogomphus Watson, 1991a: 334

'*Odon*, a tooth, referring to the dentate 11th abdominal sternite of the male.'
Gr. ὀδών = tooth + *Gomphus* (see *Austrogomphus*). {Masculine}

ofarrelli, Tonyosynthemis (Theischinger & Watson, 1986): 457

'We describe it here, and dedicate it to Professor A.F. O'Farrell, previously Professor of Zoology in the University of New England, Armidale, Australia, in honour of his 70th birthday (9 January, 1987) and in recognition of the great contribution he has made to the knowledge of the Australian Odonata.' {noun in the genitive case}

parvulus, Archiargiolestes (Watson, 1977): 198

'*parvulus* – very small' L. parvulus –a –um. {declinable adjective}

paulini, Ictinogomphus Watson, 1991a: 302

'Named after Paulinus, the first Archbishop of York, A.D. 625' [Distribution – appears to be confined to the northern part of Cape York Peninsula]. {noun in the genitive case}

paulsoni, Nannophya Theischinger, 2003: 662

'Dedication to Dennis R. Paulson (Seattle, USA) world authority on Odonata.' {noun in the genitive case}

pilbara, Nososticta Watson, 1969a

Nososticta solida pilbara Watson, 1969a: 80 becomes *N. pilbara* Watson, 1984
'Although *N. pilbara* was originally described as a subspecies of *N. solida*, it is clear that the differences between the two species are at least as great as those between some of the *Nososticta* which we now regard as distinct species. The original description of *N. pilbara* was comparative, focusing on the differences between it and *N. solida*; we here describe it fully.'

Watson (1969a: 80) 'The original description of *N. solida* could equally characterize either population; but as the description applied to eastern Australian material (Selys 1886), the north-western form must be the one described as new.' and 'The specimens from the Fortescue R. [Pilbara, WA] system are smaller than those from eastern Australia.' {noun in apposition}

pindrina, Austroagrion Watson, 1969a: 68

'Additional localities … Pindrina Spring [Sherlock River system, Hamersley Range, WA]' {noun in apposition} *pinheyi, Austroaeschna* Theischinger, 2001b: 92

First described as a subspecies of *A. unicornis*. 'Dedicated to the memory of our great colleague, Dr Elliott Pinhey.' {noun in the genitive case}

(*Pleiogomphus*) *Austrogomphus*, Watson, 1991a: 410

'Pleion, more, alluding to the apparent affinities of these gomphids to more than one subfamily.' Gr. πλεῖων = more + *Gomphus* (see *Austrogomphus*). {Masculine}

(*Pulchaeshna*) *Austroaeschna*, Peters and Theischinger, 2007: 526

Subgenus named for its type species. 'Typusart: *Austroaeschna unicornis pulchra* TILLYARD, 1909; einschließend *A. pulchra*, *A. eungella* THEISCHINGER und *A. muelleri* THEISCHINGER.' [Type species: *Austroaeschna unicornis pulchra* Tillyard, 1909, including *A. pulchra*, *A. eungella* Theischinger and *A. muelleri* Theischinger.] L. pulcher –chra –chrum = beautiful + aeschna (q.v.) {Feminine}

reevesi, Eurysticta Theischinger, 2001a: 1291

'Dedication to Deniss Reeves, president of the Australian Dragonfly Society, who was the first to draw attention to the existence of a species of *Eurysticta* in Queensland.' {noun in the genitive case}

rentziana, Eusynthemis Theischinger, 1998c: 148

'Dedication to Dr D.C.F. Rentz of Canberra whose record of the species is the only one from south of the Hunter River.' A derived adjective with the meaning of pertaining to Rentz. L. rentzianus –a –um {declinable adjective}

Rhadinosticta Watson, 1991b: 22, 23

'A new genus is needed for the Australian species hitherto referred to as *Isosticta*.'

'Name derived from the Greek *rhadinos*, slender.' Gr. ῥαδινός +-sticta which is derived from the Gr. στικτός = spotted, tattooed , but, in this case, the root refers to the second phrase of the genus *Isosticta* in which *R. simplex* and *R. banksi* were originally described, rather than necessarily being a character of the species themselves. {Feminine}

serapia, Orthetrum Watson, 1984: 1, 2

Watson (1984) named this species for St Serapia. A slave and martyr, she was the servant of St. Sabina and was responsible for the Roman noblewoman's conversion to Christianity. Both Sabina and Serapia were subsequently beheaded during the persecutions of Emperor Hadrian. {noun in apposition}

sigma, Austroaeschna Theischinger, 1982: 21

'front of synthorax dark brown with narrow pale bluish green anterior stripe which may be much broadened in dorsal half, or even be reduced to several marks, and broad bluish green S-shaped posterior stripe reaching from collar to near antealar ridge;' {noun in apposition}

Spinaeschna Theischinger, 1982: 41

The author does not provide an etymology for this gen. nov. but includes '*Spinaeschna* shows affinities with the Australian genera *Austroaeschna* Selys and *Notoaeschna* Tillyard. It is distinguished from *Austroaeschna* by having … a large spine on the supraanal plate …' L. spina = thorn, spine + aeschna (q.v.) {Feminine}

stenoloba, Tramea (Watson, 1962): 9, 15, 23

Name first made available in a checklist (p. 9) to the Dragonflies of South-western Australia, and in keys to the larvae (p. 15) and adults (p. 23).

In Watson (1967b: 398) 'the genital lobe is the narrowest found in the group, hence the specific name.' Thus Gr. στενός = narrow + λοβός = lobe. Fliedner (in litt.) advises that there is a Gr. adjective τρι- λοβός, –ον = three-lobed, the second element of which, when Latinized, becomes –lobus, –a, –um. {declinable adjective}

subapicalis, Austroaeschna Theischinger, 1982: 25

'.. inferior appendage black, broad, deep, truncate, with 2 upright dorsal teeth far from apex.' and the author (Theischinger in litt.) confirms this is the character from which the species was named, thus 'The two dorsal teeth on the epiproct of the male of *A. subapicalis* are not – as in A. *atrata* – at the epiproct end but well anterior to it (= subapical)'. L. preposition sub = under, beneath + L. apicalis –is –e = apical. {declinable adjective}

subcostalis, Austrophlebia Theischinger; 1996a: 307

'To express the close affinity with *A. costalis* (TILLYARD) as well as to indicate that the brown fasciae of the wings are less extensive than in *A. costalis* in costal field but at least equally extensive in subcostal field.'. L. preposition sub = under, beneath + L. costalis –is –e = pertaining to the ribs. {declinable adjective}

taracumbi, Nososticta Watson & Theischinger, 1984: 34

'Holotype ♂: Taracumbi Falls, Melville Island, Northern Territory.' {noun in apposition}

tenera, *Eusynthemis* Theischinger, 1995b: 305

'From Latin tener, –a –um meaning delicate.' {declinable adjective}

territoria, Austrocordulia Theischinger & Watson, 1978: 409

'Holotype ♂ and associated larval skin: Baroalba Creek … 19 km E. by N. of Mt Cahill, Northern Territory.' The author most probably deemed this to be the proper adjectival form derived from L. territorium = territory which, philologically, was not correct. {declinable adjective}

theischingeri, Hemigomphus Watson, 1991a: 331

'Named for my colleague, Günther Theischinger.' {noun in the genitive case} *tillyardi, Eusynthemis* Theischinger, 1995b: 300

'Tillyard (1910) named as "var. *pallida*" specimens from the Illawarra District of New South Wales, which he thought belonged to *E. guttata* (SELYS), and expressedly allocated infrasubspecific status to the variety. However, as Tillyard's specimens of "var. *pallida*" and other material from New South Wales and Victoria belong to a previously undescribed species, this species is dedicated to the great man who established the framework of the Australian dragonfly fauna.' {noun in the genitive case}

tonyana, Austropetalia Theischinger, 1995a: 292

'A tribute to the late Dr J.A.L. (Tony) Watson, great friend and odonatologist.' A derived adjective with the meaning of pertaining to Tony. L. tonyanus –a –um.{declinable adjective}

Tonyosynthemis Theischinger, 1998a: 140

'in memory of Prof. A.F.L. (Tony) O'Farrell (1917-1997) and Dr. J.A.L. (Tony) Watson (1935-1993), two unforgettable friends and outstanding odonatologists.' {Feminine}

undia, *Telephlebia* Theischinger, 1985: 254

'Holotype ♂, in ANIC (Type No. 9887): Queensland, Carnarvon Gorge, Aljon Falls'. Undia is an Aboriginal word meaning gorge (Reed, 2006), alluding to Carnarvon Gorge. {noun in apposition}

ursa, *Eusynthemis* Theischinger, 1999c: 375

'Ursa = Latin for "she-bear"; the species is markedly more massive than *E. ursula* (= Latin for "little she-bear") THEISCHINGER.' {noun in apposition}

ursula, Eusynthemis Theischinger, 1998b: 143

'after my granddaughter Ursula.' {noun in apposition}

watsoni, Spinaeschna Theischinger, 1982: 45

'I also wish to express my special gratitude to my friends Mr L Müller (Berowa) and Dr J.A.L. Watson (Canberra) who supported my work in many ways.' {noun in the genitive case}

(*Xerogomphus*) *Austroepigomphus* Watson, 1991a: 425

'*Xeros*, dry, referring to the dry habitats into which the ranges of both species [Z. (*Xerogomphus*) *turneri* and Z. (*Xerogomphus gordoni*)] extend.' Gr. ξερός= dry+ *Gomphus* (see *Austrogomphus*). {Masculine}

Zephyrogomphus Watson, 1991a: 432

'*Zephyrus*, the west wind, alluding to the fact that it is known only from south-western Australia.' Gr. ζέφυρος = West wind + *Gomphus* (see *Austrogomphus*). {Masculine}

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References

Brown, G.R. and Theischinger, G. (1998) *Huonia melvillensis* spec. nov., a new dragonfly from Australia (Anisoptera: Libellulidae); *Odonatologica*; **27**, 99-103.

Collins (2005) *Collins Latin Dictionary and Grammar*. Harper Collins, Glascow.

Corbet, P. S. (1999) *Dragonflies: Behavior and Ecology of Odonata*, Cornell University Press, Ithaca, NY./Harley Books, Colchester UK.

Fabricius, J. C. (1775) 'V. Vnogata'; In *Systema entomologiae*, *sistens insectorum classes, ordines, genera, species, adiectis synonymis, locis, descriptionibus, observationibus*; Libraria Kortii, Flensburgi et Lipsiae, 420-427.

Fliedner, H. (1997). Die Bedeutung der wissenschaftlichen Namen europäischer Libellen. *Libellula*, Supplement **1**, 1-111.

Fliedner, H. (2006) Die wissenschaftlichen Namen der Libellen in Burmeisters 'Handbuch der Entomologie'; *Virgo*; **9**, 5-23. [available in English translation at http://www.entomologie-mv.de/9105%20aBurmeister%20Fliedner%20englisch.pdf, accessed 11 April 2011]

Fraser, F.C. (1950) A note on the correct origin of the name *Libellula* employed in Odonata. *Entomologist's Monthly Magazine* **86**, 311-312.

Fraser, F.C. (1957) *A reclassification of the Order Odonata,* Royal Zoological Society of New South Wales, Sydney.

Hemming, F. (ed) (1958) 'Opinion 34 *Aeshna vs. Aeschna*.' In Opinions and declarations rendered by the International Commission on Zoological Nomenclature. Vol. 1 (B), London, 78-81.

ICZN (2000) International Code of Zoological Nomenclature, Fourth Edition adopted by the International Union of Biological Sciences. [available at http://www.nhm.ac.uk/hosted-sites/iczn/code/, accessed 26 May 2012]

Leach, W. E. (1815) *Entomology*. In Brewster, D. [ed.] 'The Edinburgh Encyclopaedia' Vol. 9: 57-172. [Odonata p. 136, 137], William Blackburn, Edinburgh.

Liddell, H.G and Scott, R. (1996) *A Greek Lexicon*. 9th ed with rev. suppl., Clarendon Press, Oxford.

Linnaeus C. (1758) *Systema naturae per regna tria naturae, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis*. [10th edn] [Odonata pp. 543-546] Laurentii Salvii, Holmiae.

Peters, G and Theischinger, G (2007) Die gondwanischen Aeshniden Australiens (Odonata: Telephlebiidae und Brachytronidae). *Denisia* **20,** 517-574

Rambur, P. (1842) *Histoire Naturelle des Insectes. Névroptères*, Librairie Encyclopédique de Roret, Paris.

Reed, A,W. (2006) *Aboriginal Words of Australia,* Reed New Holland, Sydney.

Selys-Longchamps, E. de (1854) Synopsis des Gomphines. *Bulletins de l'Académie royale des sciences, des lettres et des beaux-arts de Belgique* **21**, 23-112.

Selys-Longchamps, E. de. (1862) Synopsis des Agrionines, troisième légion: *Podagrion; Bulletins de l'Académie royale des sciences, des lettres et des beaux-arts de Belgique*; Series (2) **14**, 5-44.

Selys -Longchamps, E. de. (1877) Synopsis des Agrionines, 5me legion: Agrion (suite et fin). Les genres *Telebasis*, *Argiocnemis* et *Hemiphlebia*;. *Bulletins de l'Académie royale des sciences, des lettres et des beaux-arts de Belgique*; Series (2) **43**, 97-159.

Sélys-Longchamps, E. de. (1886) Révision du Synopsis des Agrionines. 1e partie (Légions Pseudostigma, Podagrion, Platycnemis et Protoneura); *Mémoires couronnés et autres mémoires publiés par l'Académie royale des sciences, des lettres et des beaux-arts de Belgique*; **38** (4), i-iv 1-233.

Theischinger, G. (1973) Eine zweite Art der Gattung *Austrocordulia* Tillyard (Odonata: Anisoptera); *Annalen Naturhistorischen Museums Wien (B)*; **77**, 387-397.

Theischinger, G. (1977) A new species of *Eusynthemis* Förster from Australia (Anisoptera: Synthemistidae); *Odonatologica*; **6**, 105-110.

Theischinger, G. (1982) A revision of the Australian genera *Austroaeschna* Selys and

Notoaeschna Tillyard (Odonata: Aeshnidae: Brachytroninae); *Australian Journal of Zoology Supplementary Series*; **87**, 1-67.

Theischinger, G. (1985) A revision of the Australian genus *Telephlebia* Selys (Odonata: Aeshnidae: Brachytroninae); *Australian Journal of Zoology*; **33**, 245-261.

Theischinger, G. (1991) In New genera, species and subspecies. pp. 20-51 In Watson, J.A.L., Theischinger, G. and Abbey, H.M. (eds). *The Australian Dragonflies*, CSIRO, Melbourne.

Theischinger, G. (1993) Two new species of *Austroaeschna* Selys from Queensland, Australia (Odonata: Aeshnidae: Brachytroninae); *Linzer Biologische Beiträge*; **25,** 805-819.

Theischinger, G. (1995a) A second species of *Austropetalia* Tillyard from Australia (Odonata: Austropetaliidae); *Linzer Biologische Beiträge*; **27**, 291-295.

Theischinger, G. (1995b) The *Eusynthemis guttata* (Selys) group of species from Australia (Odonata: Synthemistidae); *Linzer Biologische Beiträge*; **27**, 297-310.

Theischinger, G. (1996a) The species of *Austrophlebia* Tillyard (Odonata: Anisoptera: Aeshnidae: Brachytroninae); *Linzer Biologische Beiträge*; **28**, 305-314.

Theischinger, G. (1996b) The species of Lestoideinae Munz (Insecta: Odonata: Zygoptera: Lestoideidae); *Linzer Biologische Beiträge*; **28**, 315-324.

Theischinger, G. (1997a) The *Pseudagrion ignifer* complex from Australia (Odonata: Zygoptera: Coenagrionidae); *Linzer Biologische Beiträge*; **29**, 799-805.

Theischinger, G. (1997b) A new species of *Austrosticta* Tillyard from Australia (Insecta: Odonata: Zygoptera: Isostictidae); *Linzer Biologische Beiträge*; **29**, 807-810.

Theischinger, G. (1998a) T*onyosynthemis,* a new dragonfly genus from Australia (Insecta: Odonata: Synthemistidae); *Linzer Biologische Beiträge*; **30**, 139-142.

Theischinger, G. (1998b) A new species of *Eusynthemis* Förster from Australia (Odonata: Synthemistidae); *Linzer Biologische Beiträge*; **30**, 143-146.

Theischinger, G. (1998c) The *Eusynthemis guttata* (Selys) group of species from Australia (Odonata, Synthemistidae) – Part 2; *Linzer Biologische Beiträge*; **30**, 147-153.

Theischinger, G. (1998d) Supra-specific diversity in Australian '*Argiolestes*' (Odonata: Zygoptera: Megapodagrionidae); *Stapfia*; **55**, 613-621.

Theischinger, G. (1998e) A new species of *Griseargiolestes* Theischinger from Australia (Odonata: Zygoptera: Megapodagrionidae); *Stapfia*; **55**, 623-627.

Theischinger, G. (1999a) A new species of *Petalura* Leach from south-eastern Queensland (Odonata: Petaluridae); *Linzer Biologische Beiträge*; **31**, 159-166.

Theischinger, G. (1999b) A new gomphid species from the Kimberleys in north-western Australia (Insecta: Odonata); *Linzer Biologische Beiträge*; **31**, 369-372.

Theischinger, G. (1999c) New and little-known Synthemistidae from Australia (Insecta: Odonata); *Linzer Biologische Beiträge*; **31**, 373-379.

Theischinger, G. (1999d) Regions of taxonomic disjunction in Australian Odonata and other freshwater insects: first addendum, with the description of *Austrocordulia refracta jurzitzai* ssp.nov. (Anisoptera: Corduliidae); *Odonatologica* **28**, 377-384,

Theischinger, G. (2000) A new species of *Nososticta* Hagen from Australia (Odonata: Protoneuridae); *Linzer Biologische Beiträge*; **32**, 1175-1179.

Theischinger, G. (2001a) A new species of *Eurysticta* Watson from Australia (Odonata: Isostictidae); *Linzer Biologische Beiträge*; **33**, 1291-1294.

Theischinger, G. (2001b) Regions of taxonomic disjunction in Australian Odonata and other freshwater insects: second addendum, with the description of *Austroaeschna unicornis pinheyi* ssp. nov. (Anisoptera: Aeshnidae); *Odonatologica*; **30**, 87-96.

Theischinger, G. (2003) A new species of *Nannophya* Rambur from Australia (Odonata: Libellulidae); *Linzer Biologische Beiträge*; **35**, 661-666.

Theischinger. G. (2008) *Austroaeschna ingrid* sp. nov. from Victoria, Australia (Odonata: Telephlebiidae); *International Journal of Odonatology*; **11**, 241-247.

Theischinger, G. and Endersby, I. (2009) *Identification Guide to the Australian Odonata*;

Department of Environment, Climate Change and Water NSW, Sydney.

Theischinger, G. and O'Farrell, A.F. (1986) The genus *Austroargiolestes* Kennedy (Zygoptera: Megapodagrionidae); *Odonatologica*; **15**, 387-428.

Theischinger, G. and Watson, J.A.L. (1977) *Notolibellula bicolor*, a new libelluline dragonfly from northern Australia (Odonata: Libellulidae); *Journal of the Australian Entomological Society*; **16**, 417-420.

Theischinger, G. and Watson, J.A.L. (1978) The Australian Gomphomacromiinae (Odonata: Corduliidae); *Australian Journal of Zoology*; **26**, 399-431.

Theischinger, G. and Watson, J.A.L. (1985) The genus *Episynlestes* Kennedy (Odonata: Synlestidae); *Journal of the Australian Entomological Society*; **24**, 143-148.

Theischinger, G. and Watson, J.A.L. (1986) *Synthemis ofarrelli* spec. nov., a new corduliid dragonfly from Australia (Anisoptera); *Odonatologica*; **15**, 457-464.

Theischinger, G. and Watson, J.A.L. (1991) In New genera, species and subspecies. pp. 20-51 In Watson, J.A.L., Theischinger, G. and Abbey, H.M. (eds). *The Australian Dragonflies*, CSIRO, Melbourne.

Tillyard, R. J. (1913) On some new and rare Australian Agrionidae (Odonata); *Proceedings of the Linnean Society of New South Wales*; **37**, 404-479.

Tillyard, R. J. (1916) Life-histories and descriptions of Australian Aeschninae**;** with a description of a new form of *Telephlebia* by Herbert Campion; *Journal of the Linnean. Society (Zoology)*; **33** (222), 1-83.

Tillyard, R.J. (1917) *The Biology of Dragonflies* (*Odonata or Paraneuroptera*) Cambridge Zoological Series, Cambridge University Press, London.

Watson, J.A.L. (1958). A new species of *Petalura* Leach (Odonata) from Western Australia; *Proceedings of the Royal Entomological Society of London (B)*; **27**, 116-120.

Watson, J.A.L. (1962) *The Dragonflies (Odonata) of South-Western Australia. A guide to the identification, ecology, distribution and affinities of larvae and adults. Handbook No. 7*, Western Australian Naturalists' Club, Perth.

Watson, J.A.L. (1967a) A second species of *Lestoidea* Tillyard (Odonata: Zygoptera); *Journal of the Australian Entomological Society*; **6**, 77-78.

Watson, J.A.L. (1967b) An analysis of *Trapezostigma eurybia* (Selys, 1878) and related Indo-Australian species; *Nova Guinea, Zoology*; **36**, 377-400.

Watson J.A.L. (1969a) Taxonomy, ecology, and zoogeography of dragonflies (Odonata) from the north-west of Western Australia; *Australian Journal of Zoology*; **17**, 65-112.

Watson, J.A.L. (1969b) Australasian dragonflies described by R.J. Tillyard, with the location of types and the designation of lectotypes; *Journal of the Australian Entomological Society*; **8**, 153-160.

Watson, J.A.L. (1977). The *Argiolestes pusillus* complex in Western Australia (Odonata: Megapodagrionidae); *Journal of the Australian Entomological Society*; **16**, 197-205.

Watson, J.A.L. (1980). *Apocordulia macrops*, a new crepuscular gomphomacromiine dragonfly from south-eastern Australia (Odonata: Corduliidae); *Journal of the Australian Entomological Society*; **19**, 287-292.

Watson, J.A.L. (1984) A second Australian species in the *Orthetrum sabina* complex (Odonata: Libellulidae); *Journal of the Australian Entomological Society*; **23**, 1-10.

Watson, J.A.L. (1991a) The Australian Gomphidae (Odonata); *Invertebrate Taxonomy*; **5**, 289-441.

Watson, J.A.L. (1991b) In New genera, species and subspecies. pp. 20-51 In Watson, J.A.L., Theischinger, G. and Abbey, H.M. (eds). *The Australian Dragonflies*, CSIRO, Melbourne.

Watson, J. A. L. (1992) The affinities of *Aeshna brevistyla* (Rambur) (Anisoptera: Aeshnidae); *Odonatologica*; **21**, 453-471.

Watson, J.A.L, (1979) In Watson, J.A.L. and Moulds, M.S. (1979). New species of Australian Lestidae (Odonata); *Journal of the Australian Entomological Society*, **18**, 143-155.

Watson, J.A.L. and Arthington, A.H. (1978) A new species of *Orthetrum* Newman from dune lakes in eastern Australia (Odonata: Libellulidae); *Journal of the Australian Entomological Society*; **17**, 151-157.

Watson, J.A.L. and Moulds, M.S. (1977) A second species of *Episynlestes* Kennedy (Odonata: Chlorolestidae) from north Queensland; *Journal of the Australian Entomological Society*; **16**, 257-259.

Watson, J.A.L. and Moulds, M.S. (1979) New species of Australian Lestidae (Odonata); *Journal of the Australian Entomological Society*; **18**, 143-155.

Watson, J.A.L. and Theischinger, G. (1984) The Australian Protoneurinae (Odonata); *Australian Journal of Zoology Supplementary Series*; **98**, 1-51.

Watson, J.A.L. and Theischinger, G. (1991) In New genera, species and subspecies. pp. 20-51 In Watson, J.A.L., Theischinger, G. and Abbey, H.M. (eds). *The Australian Dragonflies*, CSIRO, Melbourne.

Williams, T.W. (2005) A *Dictionary of the roots and combining forms of scientific words*. Squirrox Press, Norfolk, England.

Ian Endersby

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Ian Endersby has published widely on a number of aspects of natural history. He was awarded the Australian Natural History Medallion in 2002 for his contributions to ornithology and entomology.

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Friends, Savants and Founders: W.B. Clarke and J.D. Dana

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Abstract

The friendship of the geologists J.D. Dana and the Rev W.B. Clarke marks an important interrelationship in Australian – US nineteenth century science. Formed when the two geologists met in December 1829 when Dana visited Australia attached to the United States Exploring Expedition of 1839-42 and Clarke was a recent arrival from Britain, the two men conducted pioneering fieldwork together in the Illawarra district of New South Wales which laid early foundations on the Colony's sedimentary deposits. Their friendship, linked through correspondence continued into their old age. Both men became leading savants in their own country and founders of key scientific institutions of science, Dana as the influential leader of geological science in the United States and Clarke as the first Vice-President of the Royal Society of New South Wales. The paper focuses an illuminating new photograph of W.B. Clarke presented to the author by his great grandson John Clarke.

Introduction

In 1964, I published a paper *James Dwight Dana in New South Wales, 1830-1840* in the *Journal and Proceedings of the Royal Society of NSW* (Mozley (1964)) which was my first foray into the history of Australian science and which centred on the geological exploration in January 1840 that Dana conducted with W.B. Clarke in the Illawarra district of New South Wales.

Dana was 26 and already the author of *A System of Mineralogy* (1837) when he arrived in Australia as a member of the visiting United States Exploring Expedition. The two vessels Vincennes and the Peacock, under the command of Lieutenant Charles Wilkes, had left Virginia in August 1838, and after eighteen months of survey of the South American coast and the Pacific Islands, including the Society Islands and the Samoan group, arrived unheralded in Sydney Harbour on 29 November 1839. Hailed as "one of the great events in the history of science in the United States", it carried six university-trained scientists, and, in the years 1838-42, the expedition would explore some fifteen hundred miles of the Antarctic coast, complete a survey of 280 islands, produce a total of 180 charts, and subsequently publish three extensive reports, by Dana, on geology, zoophytes and crustacea, later consigning an immense array of its collected natural history specimens to form the basis of the Smithsonian Institution (Viola & Margolies (1985)). The impact of this major expedition's findings has been less widely recognised than the British surveys that brought Darwin, Joseph Hooker and Thomas Huxley to Australian shores. But Dana was to leave his important mark. Remaining behind in New South Wales with two of the other scientists while the expedition conducted its Antarctic survey, Dana spent two months making fundamental determinations on Australia geology.

The Rev W.B. Clarke was himself a recent arrival in Australia in 1839, having reached Sydney with his wife and two children in May that year to take up an Anglican parish in the

Colony. Bu Clarke had studied geology under Professor Adam Sedgwick at Cambridge; he was a Fellow of the Geological Society of London, and the author of papers on the geology of Dorsetshire and the Continent when he arrived; the first trained geologist to settle in Australia. He was 41 and he cherished the firm ambition "to found a new earth for geology" in Australia. Eager to make Dana's acquaintance he was introduced by the expedition's chaplain on January 16. Thereafter the two men were much together Clarke riding out from Parramatta on 6 January 1840, some sixty miles via Appin, to meet Dana in Wollongong and to begin their joint examination of the abundant fossils in the argillaceous sandstone cliffs, the raised beach, the Kiama Blowhole and other phenomena of this striking Australia landscape. For Clarke it marked his first serious attempt to examine the geology of his adopted country, and it is his early Australian Diary (Clarke (1839-1840)) that provides the detail of their engaged and stimulating period of geologising. At the same time their journey formed the basis of a lifelong friendship between them, Dana writing Clarke in 1872: "The few weeks of intercourse which I had with you in Australia were among the happiest days of my life and I shall never forget your kindness& the scenes we enjoyed together". (Moyal (2003b) pp 904-905).

In the intervening years James Dana had produced his three monumental Reports of the expedition, Geology, Crustacea and Zoophytes, (Dana, 1839, 1851, 1852-3), and his major studies on Coral Reefs and Vulcanology. His Geology furnished findings of his Australian fieldwork in which he had independently mapped and described the rock formations between the Hunter and the Shoalhaven rivers, the sandstones around Sydney and Parramatta, the Illawarra District and Kangaroo Valley (which he had visited with Clarke), and determined these latter formations to be conformable and of Permian age (Viola & Margolis (1985) pp95-96). Dana was appointed to the Benjamin Silliman Chair of Geology at Yale College in 1850.

Clarke's first published papers relating to the fossils and age of the Australian coal beds were published, with some accord and some differences from Dana's, in 1848 (Clarke (1848)). In the intervening years, snatching time from parish duties, he had published extensively on meteorology and maritime and inland exploration in the Sydney press, and had emerged as the unofficial science communicator of the *Sydney Morning Herald* (Moyal (2003b) Bibliography, pp 1232-1236). Following the gold discoveries of 1851, he was appointed by the New South Wales government as Geological Surveyor to examine the Colony between Omeo in Victoria, and north to Ipswich (then a northern-most outpost of New South Wales), and to report on the structure and mineralogy of the country. His nineteen substantial reports to Government, edited and published in the Sydney press, identified many areas where gold was subsequently found, and made Clarke a household name.

Across the years, the two friends met in correspondence (Moyal (2003a), (2003b)). "I was much gratified to hear from you", Dana wrote Clarke in 1854. "I have been looking for the Reports of which you spoke but they have not yet come. I trust you will reap some golden results for your labours in behalf of the gold of Australia. I should enjoy very much another ride over the hills and through the valleys of the country… Will you never come to Yankee land? … Australia is the land for queer things; and therefore a grand place

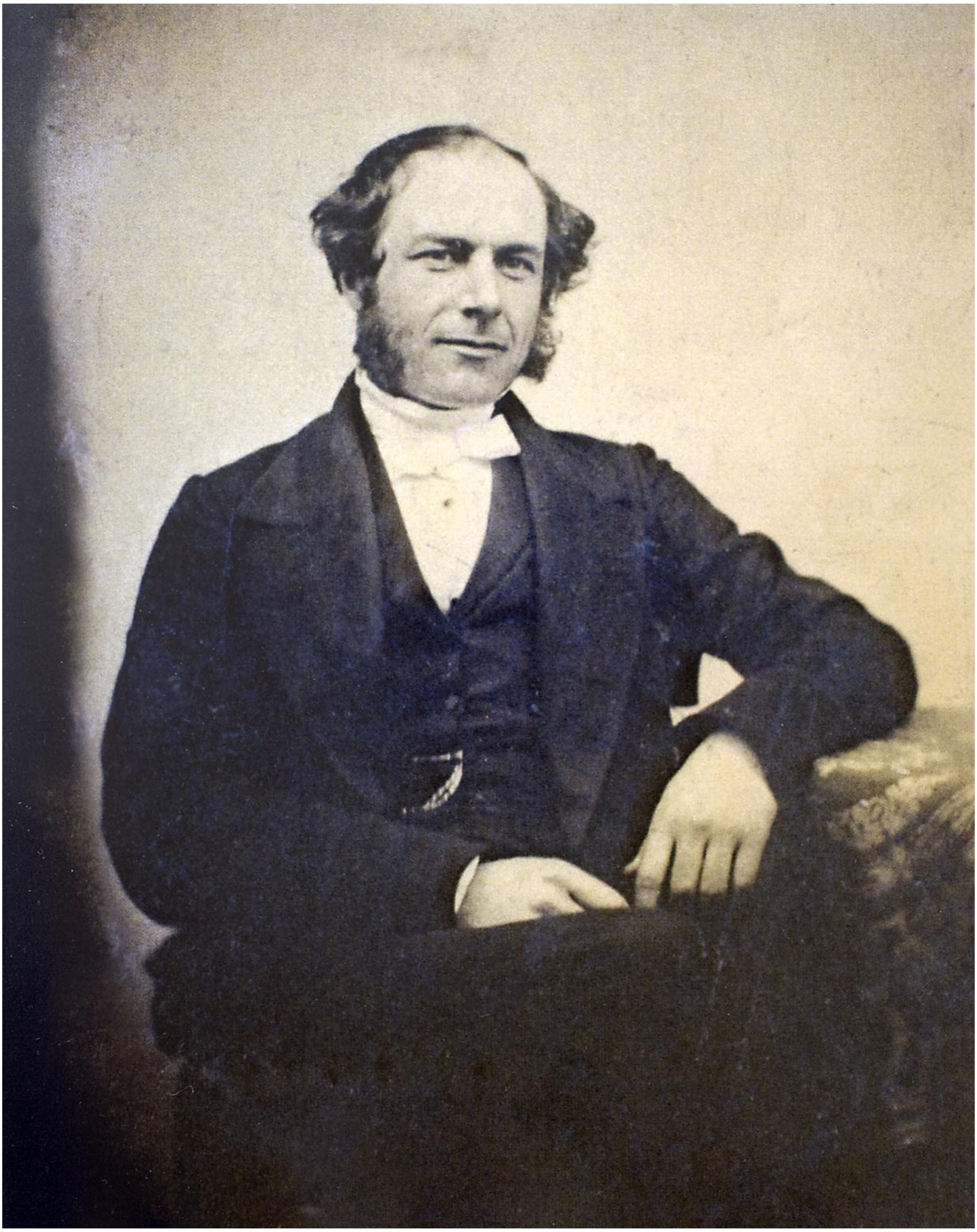

Figure 1. Rev W.B. Clarke, Australia's pioneer geologist. A newly-discovered photograph of a more youthful William Branwhite Clarke.

for scientific exploration. I should rejoice to take it up with you, if & if- and if; there, three ifs to one long one besides". (Moyal (2003a) pp408-409).

Both Dana and Clarke emerged as leading savants in their respective countries, both traversing the period when science was moving from the arena of individual inquiry to a rising professionalism. Dana became an influential teacher and researcher at Yale College, and retired as a pre-eminent national and international figurer in 1890 at the age of seventy-seven. Clarke, fifteen years his senior, had long given support and encouragement to, and shared his pioneering knowledge with, the young British-trained geologists who came to Australia in the 1850's to man the colonial geological surveys, and aided the young appointees arriving to fill scientific posts in the new universities. Importantly, as a senior contributing scientist (his *The Sedimentary Formations of New South Wales* appeared in several editions from 1867 while his papers figured in the Journal of the Geological Society of London and the Tasmanian Journal of Natural Science), he built wide networks in the growing local community of science.

A leading savant he became one of the key founding fathers of the newly-renamed Royal Society of New South Wales and served as its first Vice-President from 1867-72.

There his inaugural address in 1867 marked his open-minded approach to scientific ideas. "We must strive to discern clearly, understand fully, and report faithfully", he declared, "to love truth in all things spiritual and moral; to adjure hasty theories and unsupported conjectures; …to give our brother observer the same credit we take to ourselves but giving time for the formation of the judgment which will inevitably be given". Clarke believed that Australia would in time "throw light upon questions… imperfectly understood at home". He himself carried on a sustained correspondence with Darwin, whose work he greatly admired, although, like Dana, he rejected the evolutionary principle and, anchored in his acceptance of Divine revelation and the Christian faith, remained a Separate Creationist all his life (*Sydney Morning Herald*, 11 July 1869; Stanton, 1971).It was Charles Darwin, however, who, with William Stanley Jevons, became Clarke's sponsor for his election to the Royal Society of London in 1876.

W.B. Clarke's links with Dana, revealing in themselves, are part of a larger picture, that of Clarke as a prime communicator and networker in science. From 1840 until his death in 1878 he maintained a vast correspondence with geologists, botanists, zoologists, museum curators, land and sea explorers, astronomers, meteorologists, physical scientists, scientific governors and administrators across the Australian Colonies and New Zealand, and with leading international scientists at the centres of science in Britain, Europe and America, and he preserved this correspondence for posterity. As such he represents a key source of information on the vigorous life of science in nineteenth century Australia and its strong interrelations with science abroad.

Across my career as a historian of science I have turned to the rich Clarke Papers held in the Mitchell Library of the State Library of New South Wales as an important source for my *Scientists in nineteenth century Australia: a documentary history* (1976), *A Bright & Savage Land: Scientists in Colonial Australia* (1986) and for the collection of some 900 letters in *The Web of Science*, *The Scientific Correspondence of the Rev W.B. Clarke, Australia's Pioneer Geologist* (Australian Scholarly Publishing (2003). This research, however, has been carried out in the absence of any photograph of W.B. Clarke that reveals the character of the man, and geologists and other historical researchers have also, perforce, had to depend on depictions either of a heavily–bearded, old man or one grave image of an apparently highly disgruntled man aged about fifty-five.

Happily, in recent days W.B. Clarke's great grandson, John Clarke, now in his mid-nineties, has generously presented me with a photograph of a lively, slightly humorous, youthful William Branwhite Clarke (Figure 1), which deserves wide circulation through the Society which commemorates, in the Clarke Medal, his founding influence and his work.

References

Clarke, W.B. (1839-1940) *Diary of the Rev. W.B. Clarke*, MLMSS 139/7, Item 5. Mitchell Library, State Library of New South Wales.

Clarke, W.B. (1848) On the Genera and Distribution of Plants in the Carboniferous System of New South Wales, *Proceedings of the Geological Society London*, **4**, 60-63:

Clarke, W.B. (1848) Remarks on the Identity of the Epoch of the Coal-beds and Palaeozoic Ricks of New South Wales, *Annals of Natural History* 2nd series, **2**, 206-12.

Dana, J.D. (1849) United States exploring expedition during the years 1838, 1839, 1840, 1841, 1842 under the command of Charles Wilkes, *Geology*, vol **X**, Philadelphia,.

Dana, J.D. (1846-1849) ibid, *Zoophytes*, vol **VII**.

Dana, J.D. (1852-1855) ibid, *Crustacea* , vol. **XIII-XIV**.

Moyal, Ann (2003a)*The Web of Science. The Scientific Correspondence of the Rev. W. B. Clarke. Australia's Pioneer Geologist.* vol 1, 1836-1863, Australian Scholarly Publishing.

Moyal, Ann (2003b)*The Web of Science. The Scientific Correspondence of the Rev. W. B. Clarke. Australia's Pioneer Geologist*, vol 2, 1864-1878, Australian Scholarly Publishing.

Mozley, Ann (1964) James Dwight Dana in New South Wales, 1839-1840, *Journal and Proceedings of the Royal Society of NSW*, **97**, 185-191.

Stanton, William (1971) James Dwight Dana, *Dictionary of Scientific Biography*, vol 3, Scribners, New York, 549-554.

Viola, Herman J., Carolyn Margolis, Carolyn (eds) (1985) *Magnificent Voyagers. The U.S. Exploring Expedition, 1838-1842*. Smithsonian Institution Press, Washington.

Ann Moyal

(Manuscript received 28 March 2012; accepted 12 June 2012.)

Dr Ann Moyal is a historian with a special interest in Australian science and technology and their implications. At one stage she was Director of the Science Policy Research Centre at Griffith University, Queensland. She has published widely under the names of Ann Moyal, Ann Mozley Moyal and Ann Mozley.

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Proceedings of the Royal Society of New South Wales

The 2011 programme of events – Sydney

Friday 18 February 2011
Annual Dinner and Awards

The Patron of the Society, the Governor of NSW, Her Excellency, Professor Marie Bashir AC CVO presented a number of the Society's awards and gave the Occasional Address.

Thursday, 24 February 2011 at 6.00 pm
1188th Ordinary General Meeting – *The Four Societies Lecture*.

with the Australian Nuclear Association, Nuclear Panel of Engineers Australia and the Australian Institute of Energy.

Geothermal energy – current state of play and developments
Dr Stuart McDonnell, Chief Operating Officer for Geodynamics and
Mr Stephen de Belle of Granite Power.

Tuesday, 22 March 2011 at 6.00 pm
1189th Ordinary General Meeting – *The Two Societies Meeting*

with the Australian Institute of Physics.

Searching for nanosecond laser pulses from outer space
Dr Ragbir Bhathal, University of Western Sydney

Wednesday, 6 April 2011 at 6.00 pm
144th Annual General Meeting

Mr John Hardie was re-elected as President.

1190th Ordinary General Meeting – *the 2001 Royal Society of NSW Forum*

Belief and Science: the Belief/Knowledge Dilemma
David Malouf and Barry Jones discussed the Belief/Knowledge Dilemma.

Friday, 29 April 2011 at noon
The Dirac Lecture

with the University of New South Wales

Beauty and Truth: their intersection in mathematics and science
Robert, Lord May of Oxford OM AC FRS FAA Kt FRSN

Wednesday, 4 May 2011 at 6.00 pm
1191st Ordinary General Meeting
Heading towards the world's largest telescope: the Square Kilometre Array
Professor Michael Burton, School of Physics, University of New South Wales

Wednesday, 1 June 2011 at 6.00 pm
1192nd Ordinary General Meeting at 6.00 pm
Variation of fundamental constants from big bang to atomic clocks
Professor Victor Flambaum, School of Physics, University of New South Wales

Wednesday, 6 July 2011 at 6.00 pm
1193rd Ordinary General Meeting
Stem cells and regenerative medicine: prospects for realising the Prometheus Myth
Professor John Rasko, Centenary Institute, University of Sydney and RPA Hospital

Wednesday, 3 August 2011 at 6.00 pm
1194th Ordinary General Meeting
Schizophrenia: from neuropathology to new treatments
Professor Cyndi Shannon Weickert, School of Psychiatry, University of NSW

Wednesday, 7 September 2011 at 6.00 pm
1195th Ordinary General Meeting
Distributed small-scale production of chemicals – why and how
Professor Brian Haynes, School of Chemical and Biological Engineering, University of Sydney

Wednesday, 5 October 2011 at 6.00 pm
1196th Ordinary General Meeting
Sex in the sea: how understanding the weird and bizarre sex lives of fishes is the first step to their conservation
Prof. William Gladstone, University of Technology, Sydney

Wednesday, 2 November 2011 at 6.00 pm
1197th Ordinary General Meeting
Grid-connected energy storage: the key to sustainable energy?
Professor Tony Vassallo, School of Chemical and Biological Engineering, University of Sydney

Wednesday, 7 December at 6.30 pm
1198th Ordinary General Meeting
Scholarship Awards and Christmas Party

Tuesday, 13 December 2011 at 5.30 pm
Clarke Memorial Lecture
with the School of Geosciences, University of Sydney, the Australian Academy of Science and the Geological Society of Australia (NSW).
Professor John F. Dewey
Ordovician arc-continent collision in the Caledonian-Appalachian Orogen

The 2011 programme of events – Southern Highlands

Thursday, 17 February 2011 at 6.30 pm
Tomorrow's treatments for cancer
Dr Anita Hoskins, Garvan Institute

Thursday, 17 March 2011 at 6.30 pm
Tackling the rising problem of coeliac disease
Dr Jason Tye-Din

Thursday, 21 April 2011 at 6.30 pm
Genetics and sudden cardiac death
Dr Jamie Vandenberg, Victor Chang Cardiac Research Institute

Thursday, 19 May 2011 at 6.30 pm
Geothermal energy – current state of play and developments
Robert Hogarth, Geodynamics Ltd

Thursday, 16 June 2011 at 6.30 pm
Why did I do that?
Dr Hugh McKay

Thursday, 21 July 2011 at 6.30 pm
Who cares about the weather in space?
Dr Marc Duldig, President, Australian Institute of Physics

Thursday, 18 August 2011 at 6.30 pm
Heading towards the world's largest telescope – the Square Kilometre Array
Professor Michael Burton, School of Physics, University of New South Wales

Thursday, 29 September 2011 at 6.30 pm
Nano-optics and nanophotonics
Dr Michael Withford, Macquarie University Photonics Research Centre

Thursday, 20 October 2011 at 6.30 pm
Doctors who Kill
Dr Robert Kaplan, Graduate School of Medicine, Wollongong University

Thursday, 17 November 2011 at 6.30 pm
An update on the impact of the human genome project
Professor John Shine, Garvan Institute of Medical Research

The Royal Society of NSW Forum 2011

Wednesday 6 April 2011

Belief and science: the belief/knowledge dilemma

A discussion between Barry Jones AO and David Malouf AO

Have scientists become polarised into the believers and non-believers? Barry Jones posed this question to David Malouf and members of the Society at The Royal Society of NSW Forum 2011 on Wednesday, 6 April 2011. Reflecting upon this, Barry referred to the scientific paradigm that has emerged over the last several hundred years: scientists gather information in order to try to make sense of observed phenomena using rational analysis. Science has evolved to become not so much a matter of belief but rather of acceptance of the most sensible explanation based on the accumulation of evidence. Nonetheless, when major paradigm shifts in scientific thinking take place, there are often eminent experts who disagree and refuse to accept the new theory. This slows down the acceptance of a new paradigm but ultimately in most cases rational thought prevails.

David Malouf pointed out that non-scientists have to rely on what they are told in order to evaluate scientific theories. He pointed out the significant shift since the 18th century when early scientists put their theories to learned academies (such as the Royal Society, London) for expert examination and they determined what was accepted as scientific knowledge and what was rejected. Today, however, with the highly complex issues that society faces there are significant public policy implications that need to be resolved based on expert advice. But what do we do when the experts disagree? We are largely dependent on the media to inform us. This is further complicated because important issues are usually not just scientific in their nature but often have economic and social imperatives that commercial groups, governments and other interests seek to manipulate. Barrie commented that the sheer complexity of science has forced scientists to increasing specialisation. Furthermore, scientists are heavily reliant on research grants from government and private enterprise and this has discouraged them from entering into controversies. This is quite different to the year of only 50 or 70 years ago when renowned scientists were not afraid to comment outside their area of specific expertise.

David referred to the great advances that were made in the 17th, 18th and 19th centuries, for example, by Kepler, Newton, and Darwin. Darwin's book, *On the Origin of Species*, was very readable but most science in the 20th century has become so complex that it is not able to be so readily accessible to the layman. Furthermore, whereas once scientific advances were often made by one person, nowadays it is far more likely for the work to be attributable to a team of scientists and it is often the "front man" who gets the Nobel Prize! Science is often seen to be different from other subjects but that is not really the case – just requires a different mindset. Barry referred to the mindset underlying creationism in the US, pointing out that often a deep-seated belief cannot be shaken by debate and discourse. Nonetheless, articles on science and the relationship between science and belief in popular magazines and newspapers are important. Writers like Richard Dawkins and Stephen Hawking had not only popularised science but through their lucid writing had brought important arguments to a large public audience.

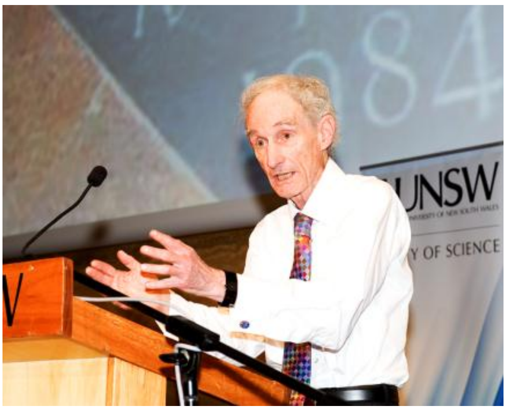
In their final comments, they concluded that the task of a scientist is to analyse inconceivably complex data and make sense of them but the public policy imperatives are driven by a media outcomes and necessarily requires the debate to be simplistic. The more we know about the complexities of nature, of the human body, the weather and so on, the more complex the questions. Science has been enormously successful and exciting in bringing an understanding in a world that we know so little about.

The Dirac Lecture

Friday, 29 April 2011

Beauty and truth: their intersection in mathematics and science

Robert Lord May of Oxford AC FRSN



On 29 April 2011, Robert Lord May of Oxford, perhaps the greatest mathematician that Australia has produced, was invested as a Fellow of the Royal Society of NSW by the Society's Patron, the Governor of NSW. Earlier that day, Lord May presented the Dirac Lecture at the University of New South Wales, jointly sponsored by the Society. The topic of Lord May's lecture was "Beauty and truth: their intersection in mathematics and science". He took us on interesting exploration of some of the important concepts of mathematics, from Euclidean geometry via the concept of imaginary numbers to the mathematics of fractals and chaos theory and the extraordinary power of mathematics to describe observed real-world phenomena. Updating the observation by Galileo, "this grand book is written in the language of mathematics, and its characters are triangles, circles and other geometric objects", Lord May pointed out that rather than triangles and circles, today the mathematical objects are more likely to be fractals and "strange attractors".

Nonetheless, as Galileo observed, and referring to the examples of Julia sets and Mandelbrot sets, there is great beauty in the elegance with which we can both describe and understand the immense complexity of the universe. He went on to explore the paradigm shift that Einstein divined from the results of the Michelson-Morley experiment that had found that the speed of light was the same for all observers. Einstein's formulation of the special theory of relativity led to a profound shift in our understanding of the relationships between momentum, mass and energy that has enabled extraordinary insights and understanding of the nature of the universe, from gravity to nuclear fission. Lord May pointed out that, regrettably, many of the great contributions do not get the recognition that they deserve. In his view, Paul Dirac was such a person – his formulation of the Dirac equation and its implication of the existence of positrons was one of the greatest steps forward in theoretical physics in the 20th century, yet his name is nowhere near as well known as that of Einstein.

Quoting Keats "beauty is truth, truth beauty – that is all ye know on earth and all ye need to know", Lord May observed: well yes, but not really.

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Realisation of a single-atom transistor in silicon

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***Editor's note**: Martin Fuechsle won one of the Royal Society of New South Wales' Scholarships in 2011. This paper describes the work that was recognised in the Award.*

Abstract

We demonstrate the fabrication of a single-atom transistor based on an individual phosphorus (P) donor atom in a crystalline silicon environment. Using a scanning tunnelling microscopy (STM)-based lithography approach, the single atom is deterministically placed with a spatial accuracy of one silicon lattice site within a gated transport device. Electronic measurements at liquid Helium temperatures and below confirm the presence of the single P donor and show that the donor's charge state can be precisely controlled via gate voltages. We observe a charging energy that is remarkably similar to the value expected for isolated P donors in bulk silicon, which is in sharp contrast to previous experiments on single-dopant transport devices. The unprecedented accuracy and high level of control over the electrostatic device properties afforded by our fabrication method opens the door for a scalable donor-based quantum processing architecture in silicon.

Keywords: silicon, quantum computation, scanning tunnelling microscopy (STM), STM lithography, single-atom devices

Introduction

Down-scaling has been the leading paradigm of the semiconductor industry ever since the invention of the first transistor in 1947 (Moore 1965). Miniaturisation of the single most important building block of modern silicon-based electronic devices – the field-effect transistor (FET) – has advanced to a stage where characteristic dimensions are approaching the 10nm-scale. In this regime, device performance can depend on the number and the discrete distribution of individual dopants (Roy 2005), i.e. foreign atoms that are added to semiconductors in small quantities to alter the electronic properties of the host material. Consequently, being able to control dopant density and distribution on a sub-nm level will be crucial for further scaling of conventional integrated nanoelectronic devices.

The realisation that "traditional" miniaturisation of conventional silicon devices by geometric scaling will soon reach its ultimate limit (set by the discreteness of matter) has lead to intensified research in alternative approaches to enhance the computational power of logic devices. One of the most exciting of these emerging technologies is quantum computation – a novel concept of computation where information is stored in coherent superpositions of suitable quantum mechanical states, so-called quantum bits or qubits. An essential requirement for the realisation of a physical qubit is the need to preserve the coherence between these basis states long enough to be able to perform logic operations (DiVincenzo (1998)).

The spin states associated with donors (i.e. dopants that donate their valence electron to the host material) in silicon are a promising candidate for the realisation of quantum logic devices due to their resilience against decoherence (Feher (1959), Tyryshkin et al. 2003)). This is essentially due to two desirable material properties of silicon (Kane (1998)), the predominance of spin-zero ^{28}Si nuclei and a small spin-orbit coupling. As a result, various silicon-based quantum computer architectures have been proposed, using either the nuclear spin (Kane (1998)), or donor electron spin (Vrijen et al. (2000)) or charge (Hollenberg et al. 2004) of individual phosphorus dopants to define the qubit. However, while considerable progress has recently been made towards spin manipulation and spin read-out (Morello et al. 2010), a remaining challenge is the scale-up of donor-based devices towards a 'useful' quantum computer comprising a large number of qubits (DiVincenzo 1998). While proposals exist for scalable two-dimensional architectures (Hollenberg et al. (2006)), these rely on vast arrays of individual impurities. To avoid spatial oscillations in the exchange coupling between neighbouring donor sites arising from the silicon bandstructure (Koiller et al. (2002)), these architectures require precise control over the location of each dopant atom within the array. A key challenge in fabricating a functional donor-based qubit is therefore the ability to pattern individual impurities in an epitaxial silicon environment with atomic accuracy.

Here, we demonstrate how STM hydrogen lithography can be used as a viable tool to overcome this challenge since it allows individual dopants to be patterned within a functional transport structure with a spatial accuracy of one lattice site.

Sample fabrication

The tool that is central to our fabrication method is a scanning tunnelling microscope (Binnig and Rohrer (1982)). Here, a fine metallic tip is scanned over a conducting surface in a raster motion in an ultra-high vacuum (UHV) environment. By plotting the measured tunnelling current between the tip and the substrate as a function of the position, it is possible to generate a map of the surface with sub-nanometre resolution. To fabricate functional devices, we use a lithographic approach based on the STM's ability to remove hydrogen (H) atoms from a silicon (Si) surface with atomic precision (Lyding et al. (1994)).

One of the key advantages of using STM for device fabrication is that it can be turned from a surface patterning tool into a non-invasive imaging tool simply by adjusting the voltage applied to the tip. This allows us to image the structure at every step of the patterning process. Fig. 1a illustrates the fabrication of the dopant-based transport structure. Here, the 3D perspective representation shows an STM image of the

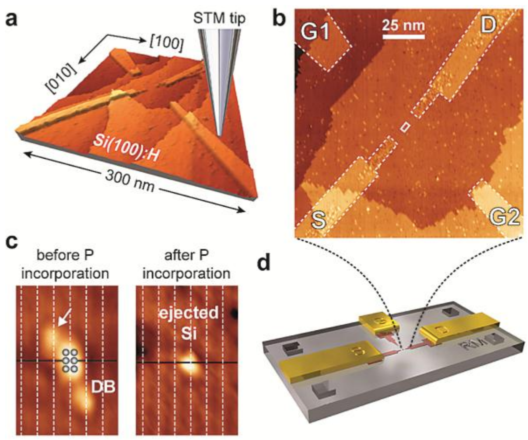

Figure 2: Incorporation pathway for a single P atom. Schematic illustration of the reaction pathway from a phosphine molecule (PH_3) to the incorporated single phosphorus atom. Upon adsorption at room temperature, PH_3 immediately dissociates to PH_2 + H (left panel) and eventually loses its remaining H atoms to neighbouring Si sites as pictured. A quick anneal at 350 °C prompts the remaining P atom to substitute for a silicon atom in the surface layer underneath, ejecting a silicon adatom in the process. It is this ejected Si atom that is observed in the STM images after the incorporation reaction (right panel of Fig. 1c). We find that 3 adjacent dimers (i.e. 6 bare Si sites) along one dimer row are necessary to incorporate exactly one phosphorus atom.

hydrogen terminated Si surface (cleaved along the (100) crystal direction) where the STM tip has been used to selectively desorb a four-terminal structure. In a subsequent step, these regions will be dosed with phosphine gas (PH_3) to form phosphorus-doped co-planar transport electrodes where the dopants are essentially confined to a single atomic plane in the perpendicular (z-) direction. Due to the high doping density (where 1 out of 4 Si atoms within the plane is replaced by a P dopant), the STM-patterned regions will conduct down to cryogenic temperatures while the surrounding substrate becomes insulating due to the thermal freeze-out of mobile carriers. This fabrication method has previously enabled the fabrication of dopant-based quantum dot structures, i.e. isolated doped islands containing a number of donors ranging from several 1000 (Fuhrer et al. (2009)) down to a few (Fuechsle et al. (2010).

Fig. 1b is a close-up of the inner device region showing the source (S) and drain (D) leads for electric measurements. These are precisely aligned to a single phosphorus donor that has been incorporated in the centre of the device (indicated by the white rectangle). Two in-plane gates (G1 and G2) are patterned on either side of the S-D transport channel to control the electrostatic potential at the position of the donor. These control gates are patterned further away (at a distance of 54 nm from the donor site) to avoid gate leakage currents from direct tunnelling to the leads.

The incorporation pathway from the adsorbed phosphine molecules on the bare Si surface to the incorporated P donors is well-understood (Wilson et al. (2004), Warschkow et al. (2005)) and occurs as a sequence of dissociative processes as illustrated in Fig. 2.

$$PH_3(ads) \rightarrow PH_2+H \rightarrow PH+2H \rightarrow P+3H \rightarrow P(incorp)$$

Here, the chemisorbed PH_3 successively loses all 3 H atoms to neighbouring bare Si sites. Upon thermal activation (by briefly annealing the substrate at 350 °C), the remaining P atom on the silicon surface incorporates into the Si surface, ejecting a silicon adatom in the process. Importantly, we find that 3 adjacent dimers (i.e. pairs of Si surface atoms) along one dimer row are necessary to incorporate precisely one P atom, in agreement with theoretical predictions (Wilson et al. (2004)) as well as previous incorporation experiments (Schofield et al. (2003)). We should note that due to the limited number of bare Si sites, only one P atom can incorporate within the

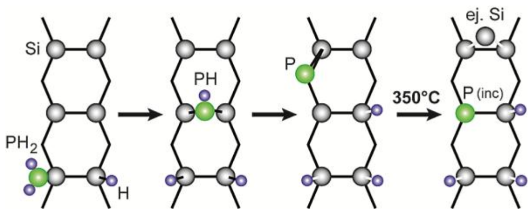

Figure 2: Incorporation pathway for a single P atom. Schematic illustration of the reaction pathway from a phosphine molecule (PH_3) to the incorporated single phosphorus atom. Upon adsorption at room temperature, PH_3 immediately dissociates to PH_2 + H (left panel) and eventually loses its remaining H atoms to neighbouring Si sites as pictured. A quick anneal at 350 °C prompts the remaining P atom to substitute for a silicon atom in the surface layer underneath, ejecting a silicon adatom in the process. It is this ejected Si atom that is observed in the STM images after the incorporation reaction (right panel of Fig. 1c). We find that 3 adjacent dimers (i.e. 6 bare Si sites) along one dimer row are necessary to incorporate exactly one phosphorus atom.

3-dimer patch, even if the surface is saturation dosed so that initially 3 PH_2 are adsorbed within the patch (see Fuechsle et al. (2012). A high-resolution image of the designated single donor incorporation site in the centre of our device is shown in Fig. 1c, both before (left panel) and after (right panel) the dosing and incorporation anneal cycle. In the left panel, we can clearly identify the required 6 H-desorbed bare Si sites. Upon dosing with PH_3 and a ~5 s incorporation anneal at 350ºC, we observe a clear change in the surface morphology (right panel). Here, the successful incorporation of a single P donor is evidenced by the observation of a single Si adatom which appears as a bright protrusion centred on a dimer row (Brocks et al. (1992)). Since the incorporated P atom substitutes for one of the 6 Si atoms within the 3-dimer site, the lateral spatial patterning accuracy of our method corresponds to ±1 Si lattice site (±3.8 Å).

The fabrication of the single-atom transistor is achieved in a two-step process: First, the intended incorporation area for the central single donor is desorbed along with the innermost parts of the leads. After an initial phosphine dosing and incorporation anneal cycle, the area is imaged again to verify the successful incorporation of a single P. Next, the in-plane gates are aligned and desorbed along with the extensions of the leads as shown in Fig. 1b. After a second dosing and incorporation anneal cycle, the entire device is overgrown with ~180 nm silicon to activate the dopants and to remove the structure away from detrimental surface effects. The low sample temperature during overgrowth (250 ºC) maintains the structural integrity of the Si:P structure and minimises dopant segregation (Oberbeck et al. (2004)). The sample is then removed from the UHV system and *ex-situ* metallic leads are defined over the STM-patterned dopant regions to form ohmic contacts to the buried dopant structure underneath, as illustrated in Fig. 1d.

Device characterisation

The transport properties of our single donor device were characterised in a $^3He/^4He$ dilution refrigerator at milliKelvin temperatures. In this temperature regime, the frozen-out intervening silicon substrate constitutes a tunnel barrier between the electrodes such that electronic transport from S to D occurs via the discrete quantum states of the donor between the leads. The inset of Fig. 3 shows the measured gate leakage current for both gates (flowing from each gate to any of the other electrodes) as a function of the applied gate voltage. We find that the available gate range is smaller for the narrower gate, G2. This is possibly due to a higher potential gradient around the tip of a narrow electrode which results in a smaller

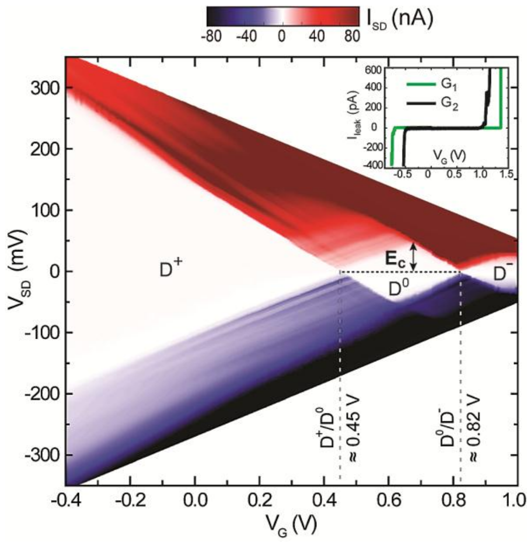

Figure 3: Stability diagram of a single-atom transistor.
The graph shows the measured source-drain current I_{SD} plotted as a function of bias voltage V_{SD} and gate voltage V_G (applied to both gates in parallel). The measurement was performed at a sample temperature of ~50 milliKelvin. In the diamond-shaped regions (centred around the V_{SD} = 0 axis), conduction through the device is suppressed due to Coulomb blockade, and the number of electrons bound to the central P atom is fixed. By applying a voltage to the gate electrodes, it is thus possible to switch the current from zero (central white regions) to a finite value (blue, red regions). We can clearly identify the three possible charge states of the donor, the ionised D^+ state, the charge-neutral D^0 state (with one bound electron), and the negatively charged D^- state, where two electrons are bound to the donor. The height of the D^0 diamond yields the charging energy E_C = 47 ± 3 meV, which is required to add the second electron to the donor. To limit the maximum current through the device, the bias voltage window was decreased as V_G was made more positive, resulting in a trapezoidal plot. Inset: The leakage current I_{leak} as a function of the applied gate voltage. The effective gate range for each gate is determined by the region where I_{leak} is negligible.

effective tunnel barrier. The leakage curves for both gates are asymmetric for positive and negative gate voltages with a significantly higher breakthrough voltage for $V_G > 0$. This is consistent with findings from previous donor-based quantum dot devices (Fuhrer et al. (2009)) and may result from partial depletion of the gate electrodes for large positive voltages.

In Fig. 3, the dc source-drain current I_{SD} is plotted as a function of the bias voltage V_{SD} and gate voltage V_G (applied to gates G1 and G2 in parallel). In this so-called stability diagram, the conductance of the single-atom transistor is zero in the diamond-shaped (white) regions due to Coulomb blockade. The latter refers to the suppression of current when the energy required to add an extra electron to a conducting island (the so-called charging energy) exceeds the thermal energy of the electrons in the leads. In our case, the island is defined by the single donor in the centre of the device. We find that the "diamond" for V_G < 450 mV does not close, i.e. the blockaded bias region increases nearly linearly with decreasing gate voltage all the way down to the lower end of the gate range. This is the expected behaviour for the positively ionised state (commonly referred to as the D^+ state) of a single P donor which cannot lose more that its one valence electron (Lansbergen et al. 2008). We thus identify the two other charge-stable regions in Fig. 3 as the charge-neutral D^0 state (for 450 mV < V_G < 820 mV) and the two-electron D^- state (V_G > 820 mV) of the donor, respectively. The current flowing from source to drain can thus be modulated by applying a voltage to the control gates, so that the device indeed behaves like a transistor.

For our single-donor device, we can directly extract the charging energy, E_C, from the transport data of Fig. 3. The charging energy is given by the height of the D^0 Coulomb diamond (Kouwenhoven et al. 1996), for which we find 47 ± 3 meV. The error arises from the asymmetry of the diamond height for $V_{SD} > 0$ and $V_{SD} < 0$ which we attribute to a different capacitive coupling of the one- and two-electron donor states to the electrodes. Importantly, the experimental value for E_C in our device is remarkably similar to the value expected for isolated P donors based on the binding energies determined by optical absorption spectroscopy (45.6 meV for D^0 and ~1.7 meV for D^-, respectively) in bulk Si (Ramdas and Rodriguez (1981)). This is in sharp contrast to previous single-dopant transport devices in silicon which have revealed charging energies that significantly differ from the bulk case (Lansbergen et al. 2008, Pierre et al. 2010, Rahman et al. (2011)). In these previous experiments, the difference was attributed either to screening effects resulting from strong capacitive coupling to a nearby gate (Lansbergen et al. 2008) or strong electric fields (Rahman et al. 2011), or to an enhanced donor ionisation energy in the proximity of a dielectric interface (Pierre et al. (2010)). However, both effects are expected to be small for our phosphorus dopant which is symmetrically positioned between the two gates (resulting in a negligible gate electric field) and encapsulated deep within a crystalline silicon environment.

The transitions between the different charge states of the donor in Fig. 3 reproducibly occur at the same gate voltages, ≈ 0.45 mV for the $D^+ \leftrightarrow D^0$ transition and ≈ 0.82 mV for the $D^0 \leftrightarrow D^-$ transition, respectively. The particular positions of the transition points along the gate axis reflect the inherent influence of the highly-doped leads in our transport device. We have quantified this influence by calculating the quantum states of the central P donor as a function of the (gate voltage-dependent) electrostatic potential defined by the electrodes (for details see Fuechsle et al. 2012). Indeed, we find that the calculated transition gate voltages are in excellent agreement with the experimental values. Furthermore, the calculations fully support the bulk-like charging energy measured in our single-donor device. The remarkable agreement between our multi-scale modelling approach and the experimental observations is testament to the high level of control over the electrostatic device properties afforded by our atomically precise fabrication method.

Conclusions

We have demonstrated the fabrication of a single-donor device in silicon, where an individual phosphorus atom is deterministically placed with sub-nm scale accuracy between dopant-based transport electrodes. Electronic measurements at cryogenic temperatures reveal that transport in our device occurs through the discrete states of the central P donor and that we can precisely control the donor's charge state via a voltage applied to the control gates. In particular, for our single-donor device we find a charging energy that is remarkably similar to the value expected for isolated donors in a bulk silicon environment. We attribute this to the absence of nearby metallic gates or interfaces and the vanishing gate electric field afforded by our device design.

With miniaturisation of classical silicon nanoelectronic devices steadily approaching the 10nm-regime, controlling the doping profile as well as the location of individual dopants will be crucial for continued developments in both quantum and classical devices in silicon. The fabrication technique presented here opens the door for novel device concepts which use single dopant atoms as their active elements. In particular, our work presents an important step towards the realisation of a scalable donor-based qubit architecture.

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References

Binnig, G. & Rohrer, H. (1982) Scanning Tunneling Microscopy; *Helvetica Physica Acta*; **55**, 6, 726-735.

Brocks, G., Kelly, P. J. & Car, R. (1992) The energetics of adatoms on the Si(100) surface; *Surface Science*; **269**, 860-866.

DiVincenzo, D. P. (1998) Real and realistic quantum computers; *Nature*; **393**, 6681, 113-114.

Feher, G. (1959) Electron spin resonance experiments on donors in silicon. 1. Electronic structure of donors by the electron nuclear double resonance technique; *Physical Review*; **114**, 5, 1219-1244.

Fuechsle, M., Mahapatra, S., Zwanenburg, F. A., Friesen, M., Eriksson, M. A. & Simmons, M. Y. (2010) Spectroscopy of few-electron single-crystal silicon quantum dots; *Nature Nanotechnology*; **5**, 7, 502-505.

Fuechsle, M., Miwa, J. A., Mahapatra, S., Ryu, H., Lee, S., Warschkow, O., Hollenberg, L. C. L., Klimeck, G. & Simmons, M. Y. (2012) A single-atom transistor; *Nature Nanotechnology*; **7**, 242–246.

Fuhrer, A., Fuchsle, M., Reusch, T. C. G., Weber, B. & Simmons, M. Y. (2009) Atomic-scale, all epitaxial in-plane gated donor quantum dot in silicon; *Nano Letters*; **9**, 2, 707-710.

Hollenberg, L. C. L., Dzurak, A. S., Wellard, C., Hamilton, A. R., Reilly, D. J., Milburn, G. J. & Clark, R. G. (2004) Charge-based quantum computing using single donors in semiconductors; *Physical Review B*; **69**, 11, 4.

Hollenberg, L. C. L., Greentree, A. D., Fowler, A. G. & Wellard, C. J. (2006) Two-dimensional architectures for donor-based quantum computing; *Physical Review B*; **74**, 4, 045311.

Kane, B. E. (1998) A silicon-based nuclear spin quantum computer; *Nature*; **393**, 6681, 133-137.

Koiller, B., Hu, X. D. & Das Sarma, S. (2002) Exchange in silicon-based quantum computer architecture; *Physical Review Letters*; **88**, 2, 027903.

Kouwenhoven, L. P., Marcus, C. M., McEuen, P. L., Tarucha, S., Westervelt, R. M. & Wingreen, N. S. (1996) *Electron transport in quantum dots*, 105-214.

Lansbergen, G. P., Rahman, R., Wellard, C. J., Woo, I., Caro, J., Collaert, N., Biesemans, S., Klimeck, G., Hollenberg, L. C. L. & Rogge, S. (2008) Gate-induced quantum-confinement transition of a single dopant atom in a silicon FinFET; *Nature Physics*; **4**, 8, 656-661.

Lyding, J. W., Shen, T. C., Hubacek, J. S., Tucker, J. R. & Abeln, G. C. (1994) Nanoscale patterning and oxidation of H-passivated Si(100)-2x1 surfaces with an ultrahigh-vacuum scanning tunneling microscope; *Applied Physics Letters*; **64**, 15, 2010-2012.

Moore, G. E. (1965) Cramming more components onto integrated circuits; *Electronics*; **38**, 114-117.

Morello, A., Pla, J. J., Zwanenburg, F. A., Chan, K. W., Tan, K. Y., Huebl, H., Mottonen, M., Nugroho, C. D., Yang, C. Y., van Donkelaar, J. A., Alves, A. D. C., Jamieson, D. N., Escott, C. C., Hollenberg, L. C. L., Clark, R. G. & Dzurak, A. S. (2010) Single-shot readout of an electron spin in silicon; *Nature*; **467**, 7316, 687-691.

Oberbeck, L., Curson, N. J., Hallam, T., Simmons, M. Y., Bilger, G. & Clark, R. G. (2004) Measurement of phosphorus segregation in silicon at the atomic scale using scanning tunneling microscopy; *Applied Physics Letters*; **85**, 8, 1359-1361.

Pierre, M., Wacquez, R., Jehl, X., Sanquer, M., Vinet, M. & Cueto, O. (2010) Single-donor ionization energies in a nanoscale CMOS channel; *Nature Nanotechnology*; **5**, 2, 133-137.

Rahman, R., Lansbergen, G. P., Verduijn, J., Tettamanzi, G. C., Park, S. H., Collaert, N., Biesemans, S., Klimeck, G., Hollenberg, L. C. L.

& Rogge, S. (2011) Electric field reduced charging energies and two-electron bound excited states of single donors in silicon; *Physical Review B*; **84**, 11, 115428.
Ramdas, A. K. & Rodriguez, S. (1981) Spectroscopy of the solid-state analogs of the hydrogen atom: donors and acceptors in semiconductors; *Reports on Progress in Physics*; **44**, 12, 1297-1387.
Roy, S. & Asenov, A. (2005) Where do the dopants go?; *Science*; **309**, 5733, 388-390.
Schofield, S. R., Curson, N. J., Simmons, M. Y., Ruess, F. J., Hallam, T., Oberbeck, L. & Clark, R. G. (2003) Atomically precise placement of single dopants in Si; *Physical Review Letters*; **91**, 13, 136104.
Tan, K. Y., Chan, K. W., Mottonen, M., Morello, A., Yang, C. Y., van Donkelaar, J., Alves, A., Pirkkalainen, J. M., Jamieson, D. N., Clark, R. G. & Dzurak, A. S. (2010) Transport Spectroscopy of Single Phosphorus Donors in a Silicon Nanoscale Transistor; *Nano Letters*; **10**, 1, 11-15.
Tyryshkin, A. M., Lyon, S. A., Astashkin, A. V. & Raitsimring, A. M. (2003) Electron spin relaxation times of phosphorus donors in silicon; *Physical Review B*; **68**, 19, 193207.

Vrijen, R., Yablonovitch, E., Wang, K., Jiang, H. W., Balandin, A., Roychowdhury, V., Mor, T. & DiVincenzo, D. (2000) Electron-spin-resonance transistors for quantum computing in silicon-germanium heterostructures; *Physical Review A*; **62**, 1, 012306.
Warschkow, O., Wilson, H. F., Marks, N. A., Schofield, S. R., Curson, N. J., Smith, P. V., Radny, M. W., McKenzie, D. R. & Simmons, M. Y. (2005) Phosphine adsorption and dissociation on the Si(001) surface: An ab initio survey of structures; *Physical Review B*; **72**, 12, 125328.
Wilson, H. F., Warschkow, O., Marks, N. A., Schofield, S. R., Curson, N. J., Smith, P. V., Radny, M. W., McKenzie, D. R. & Simmons, M. Y. (2004) Phosphine dissociation on the Si(001) surface; *Physical Review Letters*; **93**, 22, 226102.

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Effect of ultra-high acceleration of plasma blocks by nonlinear laser interaction: contributions at the University of Western Sydney

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***Editor's note**: The Royal Society of New South Wales has an active programme to engage high school and university students and to encourage a greater interest in science in young people. This paper describes a successful programme at both the University of Western Sydney and the University of New South Wales that made a valuable contribution in the "big science" arena.*

Abstract

An example is given, how a team in a growing university contributed to "big science", particularly towards a future option for a clean, unlimited and very low-cost energy source using lasers. The source is the nuclear fusion reaction in which hydrogen is converted into helium. The work described here contributes to the development of a route to nuclear fusion using ultra-high power lasers.

Keywords: Laser-plasma interaction; fusion energy by lasers; ultra-high acceleration of plasma

Introduction

A fundamental new phenomenon, the ultra-high acceleration of plasma at laser interaction, was measured by Sauerbrey (1996). This could be a key development in sourcing energy from nuclear fusion. Directly visible Doppler-effect measurements confirmed accelerations above 10^{20} cm/s^2 in agreement with numerical predictions based on the nonlinear theory for the interaction process (see figures 10.18a & b in Hora, 1981). This electromagnetic acceleration is more than 10,000 times greater than accelerations based on thermal processes due to gas-dynamic pressures was demonstrated and measured in 2011 with very large lasers with longer pulses (Park et al. (2010), Karassik et al. (2010)). The clarification and understanding of this phenomenon required several years of research. A team at the University of Western Sydney was involved and their contributions were summarised in the proceedings of a special conference held at the University of Western Sydney in cooperation with the University of New South Wales (Osman (2005), Hora et al. (2007)).

A crucial publication regarding these developments was documented in Hora et al. (2002) and is referred to extensively below. The crucial distinguishing characteristic of this phenomenon is the duration of the laser pulses. The thermally-determined acceleration from very intense laser pulses is in the nanosecond (ns) range, while the nonlinear electrodynamic interaction occurs with picoseconds (ps) pulses. The understanding of these phenomena emerged during the last 50 years with the study of intense laser pulse interaction, beginning with the discovery by Linlor (1963) of the energy of emitted ions. If the laser pulses had power, P, of less than the threshold P* of about a megawatt (MW), the interactions with targets were as predicted by classical theory. In this case, the targets were heated up to temperatures of 20,000 to 50,000 degrees, emitting ions with an energy of few electronvolt (eV) in a way that is well understood. When Linlor (1963) first used the then new "giant" laser pulses with about ten times higher power, unexpectedly, a large number of ions with thousands of times higher energy were measured. It was clear that these keV ions were not of thermal origin because they were in groups of ions with linear energy increase on the ionization number Z. This suggested that thermal equilibrium that could not have produced these energy levels. It was proposed that the generation of fast ions had to be electrodynamic in nature. This led to the discovery of the nonlinear force f_{NL} (Hora (1969a)) where a generalization of the long-known ponderomotive force was necessary with respect to the dielectric response (optical constants) of high temperature plasmas. For full understanding of the keV ions, the concept of ponderomotive self-focusing was proposed (Hora 1969b) thereby explaining the threshold P*.

Another insight was from relativity (Hora 1975a), leading to the first publication regarding MeV ions (Luther Davies et al. (1976)) explaining the large number of fast ions with energies ranging from the MeV range and up to GeV (Osman et al. (2000)). The Linlor effect was most significant in understanding the nonlinear physics of lasers.

Modelling of plasma dynamics, including the nonlinear force of laser interaction, were possible relatively simple computer models, where one-dimensional numerical results at conditions of domination by the nonlinear force against thermal processes resulted in the acceleration of plasma blocks by 10^{20}cm/s^2 (Figures 10.18a & b of Hora 1981, Fig. 1 of Hora et al. (2007)). For a long time, this acceleration could not be measured because the necessary condition of one-dimensional, plane or two-dimensional geometry was prevented in experiments due to relativistic, self-focusing generating laser beam filaments, with extremely high intensity, generating ions up to energies in the GeV range. It was not until 1996 that KrF lasers produced pulses with the Szatmari-Schäfer method (Szatmari (1994) of about 0.5 ps duration and terawatt (TW) power. This enabled the very high contrast ratio that is necessary for suppressing prepulses by more than a factor 10^8 until about 10 ps before the TW pulse interacts with the plasma.

Sauerbrey (1996) discovered by the Doppler spectral-shift experiment, that plane plasma blocks had been generated by an acceleration of 10^{20} cm/s^2 as calculated by an Australian team led by Hora (1981). The exact agreement with the nonlinear force theory was evaluated in detail (Hora et al. (2007)). Using high contrast "clean" laser pulses led to the suppression of relativistic filamentation as seen from the x-ray emission (Zhang et al. (1999)) or directed fast plasma block emission with space charge neutralized ions of extremely high current densities (Badziak et al. (1999)). The crucial paper for the explanation using the nonlinear force model (Hora et al. (2002), for ease of reference reproduced here as an Appendix) of a non-thermal, electrodynamic transfer of laser energy directly into plasma motion was reported after discussion with a number of experts in this field.

The repetition of the ultra-high acceleration (Sauerbrey (1996)) was rather difficult in view of the needed extremely high contrast for the laser pulses and the detailed properties involved. It was possible with a contrast of 10^9 and even with some lower laser pulse intensities to measure a block acceleration of $2x10^{19}$ cm/s^2 (Földes et al. (2000), Veres et al. (2004)) which could be analysed by nonlinear force action (Hora et al. (2011a)).

The importance of the many years research and interpretations (Osman (2005), Cang et al. (2005), Hora et al. (2007), Hora (2009a), Hora et al. (2011c)) can be directly seen form the ultra-fast acceleration where the nonlinear force is acting on the electron cloud within the high-density plasma instantly converts optical energy with nearly 100% efficiency into plasma motion without thermal effects where the inertia is given by the ion cloud being electrostaticly coupled to the electrons. This is the most straight forward evidence of the nonlinear force interaction process. The fundamental difference between nanosecond and picosecond (including attosecond) interaction (Krausz (2011)) is visible in the resulting ultra-high acceleration.

After the ultra-high acceleration of the then space-charged neutral plasma blocks with a ion current density of more than 10^{11} Amps/cm^2 is generated, this can be applied in the side-on ignition of solid density fusion fuel according to an updated theory by Chu (1971) and with optimized conditions (Osman et al. (2007)) by producing a fusion flame with velocities above 2,000 km/s at ignition of deuterium-tritium (DT) (Hora (2009a), Hora et al. (2011a & b)). A significant turning point in the generation of fusion energy followed when the results with DT fusion (Oliphant et al. (1934)) were extended to the nuclear fusion of protons (normal light hydrogen) with the boron isotope 11 $H^{11}B$) where less radioactive radiation is produced by the reaction, within the reactor and wasted than from burning coal per unit of generated energy. Prior to that, the experience had been that laser fusion of $H^{11}B$ is about five orders of magnitude more difficult than of DT (Hora (2009a)) and therefore was thought to be impossible. However, with the new method of ultra-high acceleration of plasma by laser, the side-on block ignition of uncompressed solid $H^{11}B$ is reduced to less than one order of magnitude more difficult than that of DT (Hora (2009), Hora et al. (2009b)). This very recent result that could lead to nuclear fusion energy with less radioactivity generation than burning coal (Hora et al. (2010)) was reported at the Royal Society of Chemistry in London (Li (2010)), referring to one of the leaders of the National Ignition Facility (NIF) laser fusion project in Livermore near San Francisco that "this has the potential of the best route to fusion energy".

The fast interaction processes of picoseconds are an essential advantage for controlled fusion energy production because it avoids thermal mechanisms with their characteristic delays and energy losses. The fast, ultra-high acceleration is based on direct and instant conversion of laser energy into plasma motion by the electrodynamic forces under negligible heating[5].

Now, for the first time, hydrogen-boron ($H^{11}B$) fusion may become possible (Hora et al. (2009a), (2010), Li (2010)). Although this option was considered early on by a number

[5] The advantage of fast processes is to reduce the problems of complex systems as noted by Edward Teller in 1952 (Teller (2001)). Teller observed that the theory of hydrodynamics, as it stood in 1890, suggested that it should not be possible to fly. After aircraft were flying, phenomena such as turbulence and other processes of complex systems came to be better understood. The stabilization of complex systems used in this new field was pioneered by May (May (1972), (2011a), (2011b)) and referred to in the context of Teller's views regarding the difficulties of controlled fusion energy generation (Hora (2011b)).

of research teams (Hora (1975b), Miley (1976), Hora (2011b)), previously it had not been thought to be possible. The potential breakthrough with $H^{11}B$ is that an approach based on ultra-fast plasma block acceleration and nonlinear force driven side-on ignition may be able to overcome a fundamental problem with DT fusion (Labaune (2011)). The problem is this: if DT fusion were to supply the Earth's energy needs, each year, 2,745 cubic meters of tritium would be needed. Currently, the only way that this could be sourced is from the equivalent amount of lithium. This amount of lithium is simply not available from current commercial sources at a resonable cost (Koonin (2011)). A further problem is that the only established processes for producing tritium from lithium release free neutrons. The neutrons decay into harmless electrons and protons (with a half-life of 881 seconds) but only if they do not interact with other materials. Interacting with other atoms could produce large amounts of radioactive waste.

Utilising fusion of $H^{11}B$ might eventually provide a solution to both problems The current method of side-on ignition with nonlinear (ponderomotive) force driven plasma blocks by ultrahigh acceleration is still embryonic. Commercial production of energy using nuclear fusion will require drawing upon the rich knowledge of plasma physics that has been developed in the last 70 years. The current well-advanced method of nanosecond laser compression for fusion using the world's largest laser (Campbell (2005), Moses (2010), Glenzer et al. (2011)) is of great importance as well as all what has been and will be learnt from magnetic confinement fusion. This achieved a the highest fusion gains reported so far with the JET experiment (Keilhacker (1999)) of an uninterrupted continuation of neutral beam fusion on larger scale is open which scheme follows well (Hora (2004); (2005)). Also the stellarator system will be important for further exploration of plasma physics after the essential breakthrough made by Grieger et al. (1981). Some new orientation in view of the nonlinear force interaction, the ultrahigh accelerations and the involved ignition could well become important developments within the existing capacities on plasma research including a concentration of several smaller activities from the past to which the contributions of team of the University of Western Sydney will be counted.

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From left to right: Dr. S. Jablonski (Poland), Prof. Jan Badziak (Poland), A/Prof Carmel Coady, Prof. Heinrich Hora (Australia), Dr. Wei Hong (China), Mrs. Rosemarie Hora (Australia), Dr. Yu Cang (China), Dr. E. Michael Campbell (USA), Dr. Hui-Chun Wu (China), Dr. Scott Wilks (USA), Dr. Sebastian Glowacz (Poland), Prof. Dieter H.H. Hoffmann (Germany), Dr Frank Stootman (Australia) Dr. Don Neely (Australia), Dr Weimin Zhou (China), Dr Reynaldo Castillo (Australia) and Dr Frederick Osman [front] (Australia).

References

Baziak, J., Kozlov, A.A., Makowski, J., Pary, P., Ryc, L., Wolowski, J., Woryna, E., Vankov, A.B., (1999) investigation of ion streams emitted from plasma produced with a high-power picosecond laser. *Laser and Particle Beams* **17**, 323-329

Campbell, E.M. (2005) *High Intensity Laser-Plasma Interaction and Applications to Inertial Fusion and High Energy Density Physics.* Doctor of Science thesis, University of Western Sydney, Australia, .

Cang, Y., Osman, F., Hora, H., Zhang, J., Badziak, J., Wolowski, J., Jungwirth, K., Rohlena, J., Ullschied, J.,(2005) Computations for Nonlinear Force driven plasma blocks by picosecond laser pulses for fusion, *Journal of Plasma Physics,* **71**, 35-51

Chu, M.S. (1972) Thermonuclear reaction waves at high densities. *Phys. Fluids,* **15**, 412-422.

Földes, I.B., Bakos J.S., Gal, K., Juhasz, Z., Kedves, M.A., Kocsis, G., Szatmari. S., & Veres, G. (2000) Properties of High Harmonics Generated by Ultrashort UV Laser Pulses on Solid Surfaces. *Laser Physics,* **10**, 264-269.

Glenzer, S., Moses, W., and 426 co-authors (2011) Demonstration of Ignition Radiation Temperatures in Indirect-Drive Inertial Confinement Fusion Hohlraums. *Phys. Rev. Letters,* **106**, 085004/1-5.

Grieger, G. And Wendelstein VII team (1981) Fusion reaction measured from stallarators. *1980 Plasma Physics and Controlled Thermonuclear Research* Vienna, IAEA, **1**, p. 173 & 185

Hora, H. (1969a) Nonlinear confining and deconfining forces associated with interaction of laser radiation with plasma. *Physics of Fluids,* **12**, 182-188

Hora, H, (1969b). Self-focusing of laser beams in a plasma by ponderomotive forces, *Zeitschrift fur Physik,* **226**, 156-160

Hora, H., (1975a) Theory of relativistic self-focuing of laser radiation in Plasmas. *Journal of the Optical Society of America,* **65**, 882-886

Hora, H. (1975b) *Laser Plasmas and Nuclear Energy* New York: Plenum Press, pp vii & 95.

Hora, H. (1981) *Physics of Laser Driven Plasmas.* New York: John Wiley

Hora, H. (2000) *Laser Plasma Physics – Forces and the Nonlinearity Principle* SPIE Press, Bellingham WA.

Hora, H., H. Peng, W. Zhang & F. Osman, (2002) New Skin Depth Plasma Interaction by ps-TW Laser Pulses and Consequences for Fusion Energy, in High Power Lasers and Applications II, Dianyan Fan et al. Eds, SPIE Proceedings N., **4914**, 37-48

Hora, H., (2004) Developments in inertial fusion energy and beam fusion at magnetic confinement. *Laser & Part. Beams,* **22**, 439-449

Hora, H. (2005) Ideal Energy Source by Mark Oliphant's Beam Fusion, *Journal and Proceedings of the Royal Society of New South Wales*, **138**, 13-29

Hora, H., Badziak, J., Read, M.N., Y.-T. Li, Liang, T.-J., Cang, Y., Liu, H., Sheng, Z.-M., Zhang, J., Osman, F., Miley, G.H., ZhangW., He, X., Peng, H., Glowacz, S., Jablonski, S., Wolowski, J., Skladanoski, Z., Jungwirth, Rohlena, K., and Ullschmied, J. (2007) Fast ignition by laser driven particle beams of very high intensity. *Phys. Plasmas*, **14**, 072701/1-7

Hora, H. (2009a) Laser fusion with nonlinear force driven plasma blocks: Thresholds and dielectric effects. *Laser and Particle Beams*, **27**, 207-221.

Hora, H., Miley, G.H., Ghoranneviss, M., Malekynia, B., Azizi, N. (2009b) Laser-optical path to nuclear energy without radioactivity: Fusion of hydrogen-boron by nonlinear forced driven plasma blocks. *Optics Communications,* **282**, 4124-4126

Hora, H., Miley, G.H., Ghoranneviss, M., Malekynia, B., Azizi, N. & He, Y.-T. (2010) Fusion energy without radioactivity: laser ignition of solid hydrogen-boron(11) fuel. *Energy and Environment Science*, **3**, 479-484

Hora, H, Miley, G.H., Flippo, K., Lalousis, P., Castillo, R., Yang, X., Malkeynia, B., & Ghoranneviss. M. (2011a) Review about acceleration of plasma by nonlinear forces from picoseond laser pulses and block generated fusion flame in uncompressed fuel. *Laser and Particle Beams,* **29**, 353-363

Hora, H. (2011b) Distinguished celebration for Professor Georg H. Miley by the University of Illinois, Urbana, Illinois, USA. *Laser and Particle Beams,* **29**, 275-278

Hora, H., Miley, G.H., Lalousis, P., Flippo, K., Gailard, S.A., Offermann, D., Fernandez, J., Yang, X., Murakami, M., Castillo, R., Stait-Gardner, T., Le Cornu, B., Julio Pozo, J. (2011c) Ultra-high Acceleration of Plasma Blocks from

Direct Converting Laser Energy into Motion by Nonlinear Forces. Proceedings International Quantum Electronics Conference IQEC Sydney 28 AUG-1 SEP 2011, 878-880

Karasik, M., Weaver, J.L., Aglitski, Y., Watari, T., Arikawa, Y., Sakaiya, T., Oh, J., Velkowitch, A.L., Zalesak, S.T., Bates, J.W., Obenschain, S.P., Schmitt, A.J., Murakami, M. & Aaechi, H. Y., (2010) Acceleration to high velocities and heating by impact using Nike KrF Laser. *Physics of Plasmas,* **17**, 056317

Keilhacker, M., (1999). High fusion performance from deuterium-tritium plasma in JET. *Nuclear Fusion,* **39**, 209-221.

Koonin, S. (2011) Inertial Fusion Energy in the US, *Proceedings of the Inertial Fusion Science (IFSA) Conference Bordeaux 12-16 Sept.* K.Mo.A.3

Krausz F. (2011) Attosecond Science: Symbiosis of Electrons and Light. Keynote Lecture at the International Quantum Electronics Conference Sydney. Proceedings International Quantum Electronics Conference IQEC Sydney 28 AUG-1 SEP 2011, 4

Labaune, C. (2011) Edward Teller Lecture: Laser-Plasma Interaction Physics and Inertial Confinement Fusion. *Proceedings of the Inertial Fusion Science (IFSA) Conference Bordeaux 12-16 Sept.* OP.Fr.A.13

Li Yuandi (2010) Nuclear power without radioactivity. *In Highlights in Chemical Technology. London: Royal Chemical Society*, **7**, issue 10.

Linlor, W.I. (1963) Ion energies produced by laser giant pulse. *Appl. Phys. Letters,* **3**, 210.

Luther-Davies, B. & Hughes, J.L. (1976) Observations of MeV ions emitted from a laser produced plasma. *Optics Communications,* **18**, 351-353.

May, R.M. (1972) Will large complex systems be stable? *Nature,* **238**, 413-414

May, R.M. (2011a) Dirac Lecture: Beauty and Truth: their Intersection in Mathematics and Science. Award of the Dirac Medal to Robert Lord May of Oxford OM AC FRS FAA Kt FRSN. *News and Views 2011: Royal Society of New South Wales.* www.nsw.royalsoc.org.au

May, R.M. (Lord May of Oxford) (2011b) Science advice and policy making. *Journal and Proceedings of the Royal Society of New South Wale,* **144**, 441 & 442, 50-57.

Miley, G.H., (1976) *Fusion Energy Conversion* Hinsdale IL.: American Nuclear Society.

Moses, E. (2010) Ignition and Inertial Confinement Fusion at The National Ignition Facility *Journal of Physics:Conference Series* 244, 12006,1-6.

Oliphant, M.L.E., Harteck, P. & Lord Rutherford (1934) Transmutation effects observed with heavy hydrogen. *Proc. Roy, Soc. London A,* **144**, 692-714.

Osman, F., Castillo, R., and Hora, H. (2000) Focusing and Defocusing of the Nonlinear Paraxial Equation at Laser-Plasma Interaction, *Laser and Particle Beam,* **18**, 73-79

Osman, F. (2005) Guest editor's preface: Workshop on fast high-density plasma blocks driven by picoseconds and terawatt lasers. *Laser and Particle Beams,* **23**, 399-400

Osman, F., Hora, H., Miley, G.H. and Kelly, J.C., (2007) New aspects of low cost energy by inertial fusion using petawatt lasers, *Journal and Proceedings of the Royal Society of New South Wales,* **140**, 423 & 424, 11-19.

Park, Hye-Sook Park and Remington, B. High energy density laboratory astrophysics. *Astrophyhsics and Space Science* (2011) in print.

Sauerbrey, R. Acceleration of femtosecond laser produced plasmas. *Phys. Plasmas* (1996), **3**, 4712.

Szatmari, S. (1994) High-brightness ultraviolet excimer lasers *Appl. Phys,.* **B 58**, 211.

Teller, E. (2001). *Memoirs.* Cambridge, MA: Perseus Publishing Perseus Publishing.

Veres, G., Kocsis, G., Racz, E. & Szatmari, S. (2004) Doppler shift of femotsecond pulses from solid density plasmas. *Applied Physics* **B 78**, 635-638.

Zhang, P., He, J.T., Chen, D.B., Li, Z.H., Zhang, Y., Wong L., Li, Z.H., Feng, B.H., Zhang, D.X., Tang, X.W., Zhang, J. (1998) X-ray emission from ultraintense-ultrashort laser irradiation. *Phys. Rev.,* **E57**, 3746-375

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Appendix

This appendix is an extract from conference proceedings at which the fundamental science underlying this approach was reported.

A full copy of the paper from the paper (Hora, H. Peng, H. S. Zhang, W. Y. Osman, F. (2002) New skin depth plasma interaction by ps-TW laser pulses and consequences for fusion energy; Proceedings of the International Society for Optical Engineering; ISSU 4914; 42-53) *is available on the Society's website.*

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New skin depth plasma interaction by ps-TW laser pulses and consequences for fusion energy

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Abstract

A new type of MeV ion generation at laser-plasma interaction has been measured based on the observation [1] that ps neodymium glass laser pulses of about TW and higher power do not produce the relativistic self-focusing based very high ion energies but more than 50 times lower energies. On top the strange observation was reported that the number of the emitted fast ions did not change at variation of the laser focus intensity by a factor 30. This can be explained by the effect that without an irradiating prepulse, a pure plane geometric skin layer interaction mechanism occurs. Neither relativistic self-focusing is possible nor the process of thermalization of quiver energy by quantum modified collisions. Following our conclusions about the difficulties for the fast ignitor concept of laser fusion, we can explain how these mechanisms can be used for studying the self- sustained fusion combustion waves as known from the spark ignition at laser fusion. We further expect an improvement of the conditions for the experiments with the highest laser fusion gains ever reported where even no pre-compression of the fusion plasma was necessary

Introduction

Lasers up to the petawatt power range and ps pulses opened a new challenge in physics. A basically new introduction of laser beams with targets was observed when pulses with powers above about TW and ps or shorter duration were irradiated. An essential difference in the emission of x-rays or vey energetic ions was dependent on the prepulses before the main short pulse arrived. While the Mourou technique for producing the very intense short pulses [6] was an essential breakthrough in the laser development since a few years, the differentiation by prepulse conditions pioneered by Jie Zhang [7, 8] is a further reason for very unexpected observations as will be shown in the following from examples of ion emission. A first interpretation of these measurements by omission of the usual relativistic self-focusing was initiated by Wang Long [9]. It turned out that the earlier known nonlinear phenomena mostly including ponderomotive and relativistic self-focusing or conditions for energetic x-ray emission in the irradiated plasmas are basically different and modified as can be concluded from the following reported theory of skin layer interaction process [2, 3, 10]. The key experiment which led to this new interaction experiment is that of Badziak et al. [1] which differs essentially from the numerous observations as e.g. [11]. In order to confirm these unusual observations, new very specific experiments were performed [2, 10] as summarized in the following on which the new theoretical results are being based.

The consequences for fusion energy generation by lasers consist in a possible clarification and refinement of the conditions of a new type of experiments which were first published by Norreys et al [5] which arrived at the highest fusion reaction gains ever published. Irradiation of 1.3 ps neodymium glass laser pulses of 6 to 15 TW on deuterium or deuterated polyethylene without any pre-compression produced a fusion gain of 3% when converted to deuterium-tritium and assuming uniform spherical neutron emission. This has to be compared with the highest gains of 1.8% measured with usual spherical irradiated on glass micro-balloons filled with deuterium-tritium gas [12] where neutrons were produced by 35 kJ frequency tripled neodymium glass laser pulses in the ns range optimized to the conditions of adiabatic volume compression [13].

The ps experiments [5] are closer to the conditions with a self-sustained fusion reaction wave front in contrast to the mentioned volume compression case [12, 13] which may lead to volume ignition at higher laser energies [13, 14] though the main aim in laser fusion is not volume ignition indeed correspond to the interesting general conditions of equilibrium of radiation, electron and ion transport from the hot into the cold plasma. The conditions of the ps experiment [5] may be different to the fusion wave conditions of spark ignition [16]. For a clarification we first outline preceding publications before discussing to the details of the new results of prepulse effects for ps laser plasma interaction.

Editor's note

There have been a number of theoretical approaches that have led to the current understanding. These are mentioned briefly below and the reader is referred to the original work for details. Several key figures mentioned in the next section are included here.

- *Fast ion interaction with plasma*
- *Nonlinear force theory for laser acceleration of plasma blocks*

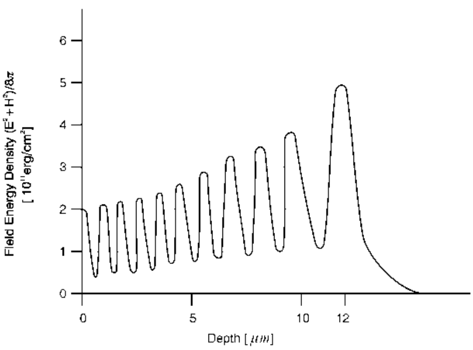

Fig. 1 Genuine two fluid calculation [21] of the electromagnetic energy density $(\boldsymbol{E}^2+\boldsymbol{H}^2)/(8\pi)$ *of the neodymium glass laser field of* 10^{16} *W/cm*^{2} *intensity after one ns in a deuterium plasma initially at rest and 100 eV temperature with an initial electron density of* 5×10^{20} *cm*$^{-3}$ *at the plasma surface increasing linearly on the depth where the critical density* 10^{21} *cm*$^{-3}$ *is reached at a distance of 12*μ*m from the surface. The maximum corresponds to an electric field amplitude 3.1 times higher than the vacuum value due dielectric swelling.*

- *Analysis of ion energies from laser irradiated targets*
  - *Fastest ion group*
  - *Second fastest ion group*
  - *Anomalous low ion energies at ps irradiation without prepulse from the experiment of Badziak* et al.

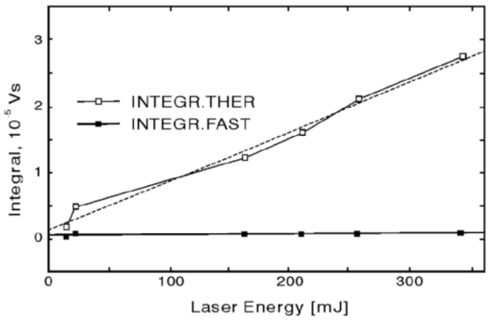

Fig. 2. Badziak et al *[1] effect of anomalous ion emission: Number of (integrated signal) emitted fast and thermal ions from a perpendicular irradiated copper target at neodymium glass laser irradiation of 1.2 ps depending on the laser pulse energy focussed to 30 wave length diameter with suppression of a prepulse by* 10^8 *for a time until less than 1 ns before the main pulse arrived.*

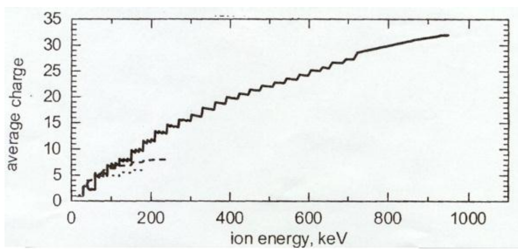

Fig. 3. Measured Charge Z and energy of the emitted fast ions from gold target irradiated by a 0.5 ns neodymium glass laser pulse of 0.7 J. energy and a focus diameter of 30μ*m together with the emitted oxygen (dashed line), carbon (dotted line) and hydrogen ions [10].*

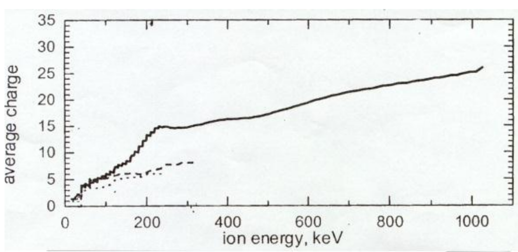

Fig. 4, Same as in Fig. 3 at the same irradiation geometry with 1.2 ps – 0.7 J laser pulses [10].

Skin layer theory for laser plasma interaction

The following explanation the few hundred times lower energy of the fastest gold ions in the 1.2 ps cases is considered as a result of a skin layer mechanism. In the experiment [10], an aspect ratio of less than 10^{-8} for the prepulse until less than 100 ps before the main pulse: no plasma could then have been produced. Only for the following 100 ps, the prepulse aspect ratio was less than 10^{-4}. It can be estimated from plasma hydrodynamics that this last part of the prepulse produced about 5 to 10 μm thick plasma in front of the target which is located in the beam focus as confirmed by the maximum x-ray emission depending on the focusing distance [1]. In view of the 30 μm diameter of the beam, the thin plasma layer in front of the target will not permit relativistic self-focusing from all knowledge of the relativistic self-focusing theory [41-42].

There seems to be an important interplay with the 10 μm thick plasma in front of the target through which the plane laser front is penetrating up the critical density and accelerating the plasma corona against the vacuum as a plane block as described in Fig. 1 while the plasma behind the critical electron density is irradiated only within the skin depth. This block of plasma of the volume of the skin depth times the whole 30 μm focus cross section is moving towards the target interior without filamentation as a plane plasma block as described, Fig. 4. The laser beam within its whole 30 μm cross section can penetrate into the superdense target plasma only one skin depth, i.e. less than or about an effective (dielelectric prolonged) wave length deep, comparable to the plane geometry calculation of Fig. 1 for the depth between 12 and 14 μm. This is an optical property and therefore independent on the laser intensity. This optically determined skin layer volume is nearly independent of the laser intensity therefore the number of fast ions does not vary when the laser intensity is changed by a factor 30 with the result that the number of fast ions is constant as measured (Fig. 2). On top, the 10 μm prepulse produced plasma layer in front of the target produced a dielectric swelling S as seen in the following by a factor of about 3.5. At these conditions the maximum electron quiver energy ε_{osc} of 19.5 eV in vacuum for the measured maximum ion energy at 300 mJ laser pulses at 8×10^{16} W/cm^2 intensity in is increased by the factor of swelling S. These conditions provided then the ideal plane wave geometry (without any filamentation) for a plane geometry acceleration of the electrons against the laser beam by the multiple of the swelling to produce the MeV maximum energy of the Au^{+26} ions

$$\varepsilon_{imax} = \varepsilon_{osc}(S-1)Z/2 \qquad (22)$$

in rather good agreement with the measurement. The details of the swelling and the temporal development of the whole nonlinear kinetics has still to be refined but this is supported by the experimental fact that the measured maximum energy (Fig. of the O^{+8} ions of 310 keV (Fig. 4) very accurately agrees with the result of the maximum energy of the Au^{+26} ions of the higher Z-ratio indicating for both ion species the fully identical collisionless and mostly electrodynamic nonlinear force acceleration mechanism by the whole volume of the block of the electron cloud. The very minor modification of this dynamics by the collision was shown [31, 34] in numerous computations using the genuine two-fluid real condition hydrodynamic code including the Poisson equation for the Coulomb effects and the nonlinear generalization of the collision frequency at high laser intensities.

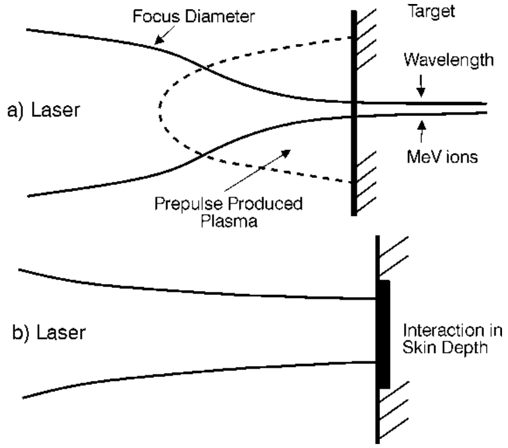

Fig. 6. Scheme for demonstration of the essential different geometry of the laser-plasma interaction volumes for subsequent volume-force nonlinear electron acceleration with separation by the ion charge Z. In case (a), the pre-generated plasma before the target causes instantaneous relativistic self focusing of the laser beam to shrink to less than a wave length diameter with very high acceleration due to the strong gradient of the laser field density. In case (b), the nearly not present or too thin plasma in front of the target permits only interaction in the skin depth with much lower ion energies but nearly ideal plasma geometry conditions treated in many details [31, 34].

The thickness of the effective Debye sheath for the electrons precursing the ions,

$$\lambda_{Deff} = 743\left(T_{eff} / n_e\right)^{1/2} \ cm \qquad (1)$$

can be estimated to be in the range of few 100 nm showing that the double layer "Coulomb acceleration" mechanism is still covered by the one fluid hydrodynamic description of the experiment of Fig. 4. Fig. 5. shows schematically how the block of accelerated plasma moving toward the laser and that toward the plasma interior have the Debye double layer surface layer of leading electrons.

The difference between the geometry self-focusing and the skin layer case is shown schematically in Fig. 6. After the clarification that the plane skin layer model explains the maximum gold and oxygen ions for the ps interaction without relativistic self focusing, we can explain also the result of Fig. 2 that under these ps irradiation without prepulse,

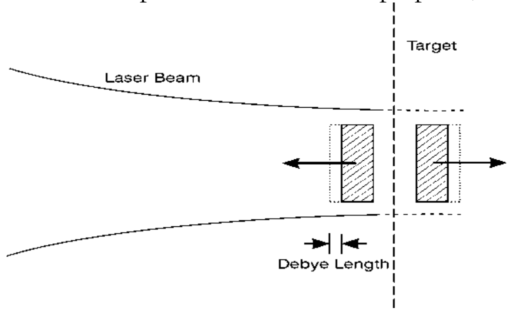

Fig.5. Scheme of skin depth laser interaction where the non-linear force accelerates a plasma block against the laser light and another block towards the target interior. In front of the blocks are electron clouds of the thickness of the effective Debye lengths, Eq. (1).

the number of the accelerated fast ions form the intensity independent skin layer volume of Fig. 6b is constant too. The deposited energy is proportional to the laser energy and the quiver energy of the electrons resulting then in the linear increase of the maximum ion energy on the intensity as measured, according to $\varepsilon_{imax} = I$.

The transition of our skin layer model towards the relativistic self focusing conditions has been seen before [8] in experiments when ps laser pulses irradiated solid targets at a systematic variation of a prepulse of an intensity where plasma is generated [7]. If the prepulse is at a too short time τ_p before the main pulse, the x-ray emission is very low in agreement with the skin layer model. As soon as the τ_p was 70 ps before the main pulse, the x-ray signals were strong and ion energies appear as expected from the relativistic self-focusing in the high-density plasma. This is due to the fact that the prepulse has produced a high-density plasma plume about two times the beam diameter above the target. This agrees with the more specific experiments for clarifying the skin layer mechanisms, presented here as a fundamentally new explanation.

For further studies it should be mentioned that it seems that the $10\,\mu m$ deep plasma in front of the target may be essential for the moderate swelling for providing the dielectric nonlinear force explosion of the two plasma blocks of Fig. 5. If an absolute exclusion of a prepulse is performed. J. Zhang expects an aspect ratio of 10^{-12} by using the second harmonics of this advanced Ti-sapphire lasers now up to 100 PW operation [8]. The conditions may appear as theoretical discussed by Mulser [30] where very low x-ray emission may be expected in connection with a peripheral drive of a fast ignitor [25]. Instead of the swelling produced dielectric expulsion of the plasma block of Fig. 5, only the ordinary radiation pressure mechanism (see Fig. 5-1 of Ref. [31]: no deconfining acceleration) will drive a plasma block of the skin layer with the ordinary radiation pressure into the depth of the target and not the increased radiation pressure due to swelling.

Consequences of the skin layer laser plasma interaction theory

Though a number of details have to be clarified for the skin layer interaction, the following new aspects for the application of the >TW-ps laser pulses with or without prepulse control may be concluded.

Laser driven ion sources

The fact that laser produced plasma with powers above P* produce million time higher ion current densities of proton beams [48] or of very highly charged ions than known from classical ion sources [2] is at least encouraging for using a laser ion source with 100 J – 10 ns laser pulses as a very competitive solution for very heavy ions in the large hadron collider (LHC) at CERN against the standard ECR source. The problems of the feeding in of the initially highly charged ions into a quadruple and linac are now under control [49] after the basic advantages of this technique had been elaborated [38]. Next step Ti-sapphire TW-PW sub-ps laser with a rather high repetition frequency up to 1 Hz are of a relatively modest costs in future. After further clarifying the parameters of the skin layer interaction. It should be possible to produce the highly charged ion blocks moving with rather low internal temperature but with high ion energy in a very directed way into the pre-amplifiers of the accelerators with an enormous increase of accelerator properties and initially very high charged heavy ions.

Nuclear physics applications

Very recently it was discovered that laser pulses of ps or shorter duration with powers of few TW only produced highly charged ions and gammas of up to 100 MeV energy [50]. In most of these experiments it was not necessary to carefully control the prepulses. If the mentioned highly energetic particles and gammas were produced using relatively low laser powers of few TW only, it can be assumed that no high aspect ratio may have been used and that relativistic self-focusing has produces the generation of the very intense and high energy particles for the short time of ps leading to a basically new dimension of nuclear research.

Laser fusion following the experiment of Norreys et al.

The very high gain laser fusion experiments of Norreys et al [5] was mentioned in the beginning. We discuss now the consequences for possible improvements using the presented skin layer interaction. Assuming similar conditions for both experiments of 1998 and 2001 [5, 47] we explained why relativistic self-focusing was avoided and only the quiver-collision hot electron generation produced the half GeV lead ions. Very probably a rather stronger prepulse was involved. If the prepulse could be controlled to a very last stage as in the Badziak et al experiments [1, 10] or by the techniques of J. Zhang [7, 8] it may be possible to reduce the hot electron generation and to achieve the nonlinear force driven highly directed block motion of plasma (Fig. 5). For generation of reaction front for ion interpenetrating [4], ion energies of about 100 keV are optimized. Instead of the conditions for half GeV ion acceleration [47] one may defocus the high aspect ration ps pulse to a large cross section with PW pulses with final intensity of few 10^{17} W/cm^2 specified with a modest swelling similar to Fig. 1. The block of DT plasma towards the target has then a (space charge neutralized) ion current density of 10^{10} Amp/cm^2 such that pulses of about 10kJ will reach the condition of few 10^6 J/cm^2 for generation of the reaction front as explained before [4]. This may then lead to a very high gain energy production even possible for a combination with the dream fuel pB(11) [51].

It is no question that for such a scheme an enormous amount of work is necessary to clarify the just elaborated skin layer interaction mechanism [2, 10] as initiated by the experiments by Badziak et al [1] and Zhang et al [7] and the special attention to prepulse control and necessary high quality picosecond (or shorter) laser beam generation. The computational analysis of the swelling and the nonlinear force acceleration as expressed in Fig. 1 is then a further extensive task. Furthermore the earlier described interpenetration process initially designed for the ANTARES carbon dioxide laser [4] and now open for the laser beams from the Mourou technique [6], needs a much more detailed clarification. Summarising this all it is by far not certain that the just explained extension of the Norreys et al experiment [5] along the described lines will lead to the kings way for the laser fusion power station but it seems to be interesting to consider this possibility apart from unique new physics to be gained with this research.

References

[1] J. Badziak, et al, Laser and Particle Beams 17, 323 (1999)

[2] H. Hora, J. Badziak, F.P. Boody, R. Höpfl, K. Jungwirth, J. Kraska, L. Laska, P. Parys, M. Pfeifer, K. Rohlena, J. Skala, J. Ullschmied, J. Wolowski, and E. Woryna, Optics Comm. 207, 333 (2002)

[3] H. Hora, H. Peng, W. Zhang, and F. Osman, Bull. Am. Phys. Soc. 47, 879 (2002)

[4] H. Hora, Atomkernengie-Kerntechnik 42, 7 (1983)

[5] P.A. Norreys, A.P. Fews, et al Plasma Physics and Controlled Fusion 40, 175 (1998)

[6] G. Mourou and R. Umstadter, Scienfic American, May 2002

[7] P. Zhang, J.T. He, D.B. Chen, Z.H. Li, Y. Zhang, J.G. Wang, Z.L. Li, B.H. Feng, X.L. Zhang, X.W. Tang, J. Zhang, Phys. Rev. E 57, 3746 (1998)

[8] Jie Zhang, private communication, Beijing, May 2002

[9] H. Hora and Long Wang, Contributed paper at the Reguinal Plasma Physics College, Islamabad, February 2001

[10] H. Hora, F. Osman, R. Höpfl, J. Badziak, P. Parys, J. Wolowski, E. Woryna, F. Boody, K. Jungwirth, B. Kralikowa, J. Kraska, L. Laska, M. Pfeifer, K. Rohlena, J. Skala, J. Ullschmied, Czechoslovak J. Physics 52, Supplement D CD-ROM in July issue, D349 (2002)

[11] E. Woryna, J. Wolowski, B. Kralikowa, J. Kraska, L. Laska, M. Pfeifer, K. Rohlena, J. Skala, V. Perina, R. Höpfl, and H. Hora, Rev. Scient. Instrum. 71, 949 (2000)

[12] J.M. Sources, R.L. McCrory et al, Phys. Plasmas 3, 2108 (1996)

[13] H. Hora, H. Azechi, Y. Kitagawa, K. Mima, M. Murakami, S. Nakai, K. Nishihara, H.

Takabe, C. Yamanaka, M. Yamanaka, and T. Yamanaka, J. Plasma Physics 60, 743 (1998),
[14] H. Hora, and P.S. Ray, Zeitschr. F. Naturforschung A33, 890 (1978)
[15] E. Storm, J. Lindle, M. Campbell, T.P. Bermat, I.W. Coleman, J.L. Emmett, et al, LLNL Livermore Report No. 47312 (1988)
[16] G.S. Fraley, F.J. Linebur, R.J. Mason and R.L. Morse, Physics of Fluids 17, 474 (1974)
[17] H. Azechi, et al. Laser and Particle Beams 9, 167 (1991)
[18] H. Hora, S. Nakai German Patent Application Disclosure DE199 11 386
[19] K.A. Brueckner and S. Jorna, Rev. Mod. Physics, 46, 325 (1974)
[20] M.S. Chu, Phys. Fluids 15, 413 (1972)
[21] H. Hora, P. Lalousis and S. Eliezer, Phys. Rev. Lett. 53, 1650 (1984)
[22] S. Eliezer and H. Hora, Phys. Repts. 172, 339(1989)
[23] H. Hora, Nuovo Cimento B64, 1 (1981)
[24] D. Gabor D, Proc. Royal Soc. London A 213 73 (1953); P.S. Ray and H. Hora, Nuclear Fusion 16, 535(1976)
[25] M. Tabak et al. Physics of Plasmas 1, 2010 (1993)
[26] A.P. Fews. P.A. Norreys et al Phys. Rev. Letters 73, 1801 (1994)
[27] H. Hora, H. Azechi, et al. AIP Conference Proceedings No. 406, G.H. Miley and E. Michael Campbell eds. (Am. Inst. Physics, New York 1997) p. 165
[28] M.H. Key, Nature 412, 775 (2001)
[29] H. Hora, Nature 333, 337 (1998); H. Hora, M. Hoels, W. Schied, J.W. Wang, Y.K. Ho, F. Osman and R. Castillo, Laser Particle Beams 18, 135 (2000)
[30] S. Heim and P. Mulser, Phys. Rev. Letters 86, 1015 (2001)
[31] H. Hora, Laser Plasma Physics – Forces and the Nonlinearity Principle (SPIE Books, Bellingham WA, 2000)
[32] H. Hora, Phys. Fluids 28, 3706 (1985)
[33] T. Rowlands, Plasma Physics and Controlled Fusion32, 297 (1990)
[34] H. Hora, Plasmas at High Temperature and Density (Springer Heidleberg 1991; S. Roderer, Regensburg 2000)
[35] W.I. Linlor, Appl. Phys. Lett. 3, 210 (1953)
[36] H. Hora, Phys. Fluids 12, 181 (1969)
[37] A.W. Ehler, J. Appl. Phys. 46, 2464 (1975)
[38] H. Haseroth and H. Hora, Laser and Particle Beams 14, 393 (1996)
[39] H. Hora, Zeitschr.f.Physik, 226, 159 (1969)
[40] M.C. Richardson and A.J. Alcock, Applied Physics Letters 18, 357 (1971)
[41] H. Hora, J. Opt. Soc. Am. 65, 882 (1975); D.A. Jones, E.L. Kane et al. Phys. Fluids, 25, 2295
[42] T. Häuser, W. Scheid and H. Hora, Phys. Rev. A45, 1278 (1992)
[43] R.L. Morse, and C.W. Nielson, Physics of Fluids 16, 909 (1973); L.M. Wickens, and J.E. Allen, J. Plasma Physics 22, 167 (1979)
[44] J. Wolowski, J. Farny, L. Laska, K. Masek, P.Parys, K. Rohlena, and E. Woryna, Laser Interaction and Related Plasma Phenomena, APS Conference Proceedings No. 406, G.H. Miley and E.M. Campbell eds., (Am. Inst. Phys. New York 1997) p. 510
[45] J. Badziak et al. J. Phys. D34, 1855 (2001)
[46] S.J. Gitomer et al. Phys. Fluids 29, 2679 (1986)
[47] E.L. Clark, K.Krushelnik, M. Zepf, M. Tatasakis, M. Machacek, M.I.K. Santala, I. Watts, P.A. Norreys, and A.E. Dangor, Phys. Rev. Letters, 85, 1654 (2001)
[48] S.P. Hatchett et al, Physics of Plasmas 7, 2076 (2000); K. Nemetz, A. Maksimchuk et al. Applied Phys. Letters 78, 583 (2001)
[49] H. Kugler, M. Makarov, Yu. Satov, S. Kondrachev (unpublished, CERN Geneva, June 2002); N. Lisi, C. Meyer, and R. Scrivens, Laser and Particle Beams 19, 647 (2001)
[50] K.W.D. Ledingham et al, Phys. Rev. Letters 84, 899 (2000); M. Roth, M.H. Key et al, Phys. Rev. Letters 86, 436 (2001); H. Schwoerer, P. Gibbon, S. Duesterer, K. Behrens, C. Ziener, C. Reich, and R. Sauerbrey, Phys. Rev. Letters 86, 2317 (2001); W.P. Leemans et al. C.R. Acad. Sci. Paris, t.1, Series IV, 279 (2000)
[51] H. Hora, German Patent Application 1033 08 515.3 (28.2.200

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Thesis abstract

Development of instantaneous temperature imaging in sooty flames

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Temperature is a dominant parameter in combustion processes. Temperature characterises the enthalpy of reaction and controls many of the important chemical and physical processes, which also influence composition of the combustion products. Laser diagnostics are the preferred tool for measurement of many flame parameters, including temperature. The laser-based diagnostic techniques have the potential to provide in situ, nonintrusive, temporally, and spatially precise, information that is unrivalled by alternative methods. A variety of laser-based thermometry techniques have been developed. However, most of these techniques are best suited to clean combustion environments and have restrictions in the presence of particles, such as dust, coal, biomass and soot. This limits the capacity to investigate and understand many systems of practical significance.

Two-line atomic fluorescence (TLAF) is a laser thermometry technique based on the relative temperature-dependent population of two energy levels within an atomic species. The temperature is deduced from the ratio of the fluorescence signals associated with the transitions. Not only does TLAF offer two-dimensional measurements, the inelastic nature of the TLAF technique, when spectrally shifted emissions are used, enables filtering to be used to minimize interferences from spurious scattering, thus allowing measurements to be performed in particle-laden environments. Of the atomic species available, indium seeded into the flame has been identified as a suitable thermometry species for TLAF. The TLAF technique in the linear excitation regime has previously been demonstrated to be feasible in sooty environments. Under such conditions, the linear TLAF results are plagued by low signal-to-noise ratio (SNR), thus preventing useful single-shot imaging that requires higher SNR.

This dissertation reports on the single-shot temperature imaging in sooty flames, based on the development of two-line atomic fluorescence in the nonlinear excitation regime (NTLAF), with neutral indium atoms as the seeded thermometry species. A series of systematic studies have developed the NTLAF and demonstrated its applicability to a range of flames, especially flames containing soot. Aspects of NTLAF that have been investigated include seeding concentration, linearity limits, effect of flame stoichiometry (Medwell et al. (2009)), effect of soot (Chan et al. (2011a)), and a comparison of different solvents (Chan et al. (2010)). The NTLAF thermometry technique has been shown to provide temperature measurements that are comparable with alternative techniques (Medwell et al. (2010)). More recently, with the use of an optimal solvent, it has been demonstrated that the single-shot uncertainty of the technique can be reduced down to ~60 K (Chan et al. (2011b)). The technical feasibility of the NTLAF technique to be used concurrently with laser-induced incandescence (LII) technique, to provide simultaneous single-shot imaging of temperature and soot concentration has also been demonstrated (Chan et al., 2011b).

References

Medwell, P.R., Chan, Q.N., Kalt, P.A.M., Alwahabi, Z.T., Dally, B.B. and Nathan, G.J., (2009), Development of temperature imaging using two-line atomic fluorescence, *Applied Optics*, 48, 6, 1237-1248.

Chan, Q.N., Medwell, P.R., Alwahabi, Z.T., Dally, B.B. and Nathan, G.J., (2011a), Assessment of interferences to nonlinear two-line atomic fluorescence (NTLAF) in sooty flames, *Applied Physics B*, 104, 189-198.

Chan, Q. N., Medwell, P.R., Kalt, P.A.M., Alwahabi, Z.T., Dally B.B. and Nathan, G.J., (2010) Solvent effects on two-line atomic fluorescence of indium, *Applied Optics*, 49, 8, 1257-1266.

Medwell, P.R., Chan, Q.N., Kalt, P.A.M., Alwahabi, Z.T., Dally, B.B. and Nathan, G.J., (2010), Instantaneous temperature imaging of diffusion flames using two-line atomic fluorescence, *Applied Spectroscopy*, 64, 2, 173-176.

Chan, Q.N., Medwell, P.R., Kalt, P.A.M., Alwahabi, Z.T., Dally, B.B. and Nathan, G.J., (2011b) Simultaneous imaging of temperature and soot volume fraction, *Proceedings of the Combustion Institute*, 33, 791-798.

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Thesis abstract

Patterns of telomere length change with age in aquatic vertebrates and the phylogenetic distribution of the pattern among jawed vertebrates

Christopher Izzo

Abstract of a thesis for a Doctorate of Philosophy submitted to The University of Adelaide, South Australia, Australia

In this thesis, I aimed to assess the application of telomeres, the protective caps that the ends of chromosomes, as a novel age determinate for aquatic vertebrates in order to overcome the limitations of the commonly applied increment based ageing methodology. More specifically, I sought to correlate the natural changes in telomere lengths (*TeL*) with chronological ageing in multiple species of teleosts, chondrichthyans, and a species of pinniped.

Species of teleosts and chondrichthyans had significantly different rates of *TeL* change with age and these rates of change were strongly correlated with longevity. *TeL*-at-age relationships were characterised by a large degree of inter-individual variability of *TeL* within all age classes, limiting telomeres to at best assigning broad age classes. Alternatively, telomeres may be better suited as indices of animal condition, by providing a measure of the 'physiological' age of individuals, reflecting the accumulated effects of ageing and stress events throughout life; thus animals with shorter telomeres in spite of their younger chronological age may be biologically old. In total, five of the nine teleosts examined showed significant *TeL*-at-age relations, as did the species of pinniped. None of the six chondrichthyan species showed this relationship.

Interestingly, these findings highlight that patterns of *TeL* change with age are highly variable within the jawed vertebrates (gnathostomes) – thus, telomere change cannot be characterised by a single pattern for all gnathostomes. In fact, there are three patterns of *TeL* change with age in the gnathostomes:

(i) declining *TeL*
(ii) increasing *TeL*; and
(iii) no significant change in *TeL*.

However, identifying the selective factors responsible for the assignment of and transitions between states of *TeL* change with age are hampered by a lack of the understanding of the overall evolutionary patterns of *TeL* change.

Therefore, I sought to outline the phylogenetic distribution of patterns of *TeL* change with age in the gnathostomes to determine the evolutionary origin(s) of this trait. Two alternative hypotheses for the evolution of *TeL* change were tested by ancestral state reconstruction in a set of 40 gnathostomes. The most likely/parsimonious pattern of *TeL* change in the common ancestor to all gnathostome lineages was determined, i.e. *TeL* change with age was not present ancestrally and has since evolved independently in divergent gnathostome lineages, with some secondary losses. I was also able to elucidate the evolutionary history of transitions between patterns of *TeL* change within the available gnathostome lineages, with the birds and teleosts displaying the highest rates of evolutionary lability of patterns of *TeL* change with age through repeated transitions/reversions from the ancestral state.

This macro-evolutionary analysis identified relatively rapid evolutionary patterns of *TeL* change with age in two gnathostome clades. However, as highlighted by the high inter-individual variability of *TeL* within all age classes, furthering an interpretation of the biological and biochemical causes and consequences of variable patterns of *TeL* change will require a focus at the species level and a shift to following individuals through out their lifetime.

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Thesis abstract

Causes and consequences of sleepy lizard, *Tiliqua rugosa*, social networks

Stephan T. Leu

Abstract of a thesis for a Doctorate of Philosophy submitted to Flinders University, South Australia, Australia

An important aim of behavioural ecological research is to develop a unified model to explain the determinants of the great variety of animal social groups, including their maintenance and evolution. Social reptile species, lizards in particular, are increasingly used to systematically test social behaviour theory, expanding its application beyond the usually studied birds, mammals and social insects and better describing the natural variability of sociality. I contributed to this important expansion by investigating the ecological and evolutionary processes that drive the social behaviour in the unusually social Australian sleepy lizard, *Tiliqua rugosa*.

I used modern Global Positioning System technology to investigate socially relevant behaviours that are rarely seen by direct observation in this species. Using social network analysis techniques, I identified the social organisation as pair-living. Detailed continuous data records supported previous findings of pair-living behaviour from snapshot observations, but also revealed that social pairs remained associated after mating had finished, an intriguing behaviour since reproduction is a strong driving force in pair living. (Leu et al. (2010a)).

Further analysis of the pair behaviour showed that predominantly males, but also females, initiated the reunion of the social pair after temporary natural separations. But, males appear to experience higher costs of pair living than females because they initiated temporary separations of the pair more frequently than females. Sex biased activity, males showed higher movement activity and remained active for longer each day, may be an important mechanism to mitigate the higher costs of pair living for males, such as lost extra-pair matings and within pair competition for food. (Leu et al. (2011a).

Ecological factors influence social behaviour, for example refuge availability may determine refuge sharing frequencies. Sharing refuges of otherwise solitary individuals during periods of inactivity is an integral part of social behaviour and has been suggested to be a potential precursor to more complex social behaviour. To test this assumption I compared social networks for active versus inactive lizards, both for social pair partners and for non-pair members of the social neighbourhood. However, I did not find evidence that refuge sharing may have been the evolutionary pathway to sleepy lizard social behaviour (Leu et al. (2011b)).

Social associations and interactions with other individuals of the species may facilitate the development of tolerance and cooperation. However, they may also increase the risk of parasite transmission, which negatively affects host fitness. I investigated this for ticks, important parasites that are indirectly transmitted at refuge sites. I found that sleepy lizard individuals that frequently used their neighbours' refuges were highly connected within a tick transmission network, had higher cross-infection risks and suffered from higher tick loads. Furthermore, increasing the number of refuges each lizard uses may be an important defence mechanism against ectoparasite transmission. (Leu et al. (2010b)).

Investigating these different aspects of social behaviour, this study extends our knowledge of sociality in lizards and provides valuable comparative information for a better understanding of the generality of animal social behaviour.

References

Leu, S.T. Bashford, J., Kappeler, P.M., Bull, C.M. (2010a) Association networks reveal social organization in the sleepy lizard; *Animal Behaviour*; **79**, 1, 217–225

Leu, S.T., Kappeler, P.M., Bull, C.M., (2010b) Refuge sharing network predicts ectoparasite load in a lizard; *Behavioral Ecology and Sociobiology*, **64**, 1495-1503.

Leu, S.T., Kappeler, P.M. Bull, C.M. (2011a) Pair-living in the absence of obligate biparental care in a lizard: trading off sex and food? *Ethology*; 117, 9, 758–768.

Leu, S.T., Kappler, P.M., Bull, C.M., (2011b) The influence of refuge sharing on social behaviour in the lizard *Tiliqua rugosa*; *Behavioral Ecology and Sociobiology*, **65**, 4, 837-847.

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Thesis abstract

Insular toponymies: pristine place-naming on Norfolk Island, South Pacific and Dudley Peninsula, Kangaroo Island, South Australia

Joshua Nash

Abstract of a thesis for a Doctorate of Philosophy submitted to University of Adelaide, South Australia

Documenting patterns of pristine toponymy, or toponymic knowledge in locations where people remember the locations and histories of people and events associated with extant placenames, is a worthwhile endeavour in linguistically pristine island environments, i.e. isolated, small island situations that have witnessed recent human habitation and that were uninhabited prior to colonisation. This study used the toponymy of Norfolk Island, South Pacific, an external territory of Australia as a main study and compared it to the toponymy of Dudley Peninsula, Kangaroo Island, South Australia. The principal research question for the study sought to establish whether the difference between official and unofficial toponyms and processes of toponymy in the two island environments was a consequence of the degree of linguistic, cultural and ecological embeddedness of these toponyms and toponymic processes.

The linguistic situation on Norfolk is diglossic: English and Norf'k, the language of the descendants of the *Bounty* mutineers, are spoken. Norfolk is a political and cultural anomaly in Australia and its anomalous nature is depicted in the unclear boundaries not only of its human history but also in the blurring of boundaries in its toponymic history. This is a result of distinct and changing patterns of land use and differing linguistic and toponymic perceptions of the same geographical space.

Dudley Peninsula is less remote and less politically and culturally anomalous than Norfolk and was selected as an island comparative study to contrast principles of unofficial toponymy with unofficial Norfolk Island toponymy. Employing a comparative method also made it possible to ascertain the extent to which a nexus and theory of pristine toponyms, transparent versus opaque toponymic histories and the official versus unofficial status of toponyms is practical across two island toponymic case studies.

Primary Norfolk data were coupled with secondary archival data (n = 1068), analysed and compared to the unofficial Dudley Peninsula data (n = 253). The results of this study reveal that the differences between official and unofficial toponyms can be accounted for by the establishment of typology involving four toponym categories:

i. common colonial forms;
ii. official and unofficial descriptive toponyms;
iii. unofficial names commemorating local people; and

iv. unofficial and esoteric names commemorating local events and people.

This thesis puts forward a claim delineating a broad continuum within and between 'conscious toponymic wisdom' and 'unconscious toponymic wisdom', which is realised differently in the two locations. There is a tendency for more 'conscious toponymic wisdom' within Norfolk Island's toponymic ethos as compared to Dudley Peninsula's more 'unconscious toponymic wisdom'. Engaging in ecolinguistic fieldwork is a productive means to foreground the significance of local, unofficial and esoteric toponymic knowledge by working intimately with informants.

In conclusion, this thesis argues that the concept of *insular toponymies*, i.e., undertaking an analysis of toponyms based predominantly in the documentation and analysis of primary toponymic field data, was appropriate to describe the nature of toponymy in isolated and insular island societies. This study puts forward the term *toponymic ethnography* as a worthwhile concept within the parameters of linguistic and cultural research in toponymy

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Thesis abstract

Investigation into the molecular function of the neuronal Hu RNA binding protein, HuCsv1

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Abstract of a thesis for a Doctorate of Philosophy submitted to the University of Adelaide, Adelaide, South Australia

Of the four Hu genes found in most vertebrates (HuA, HuB, HuC and HuD), all except HuA exhibit mRNA and protein expression that is essentially restricted to post-mitotic neurons of the developing and adult nervous systems. Spatial and temporal examination of individual "neuronal Hu" (nHu = HuB, HuC and HuD) proteins in brain tissue suggests nHu proteins may play a functional role during neuronal differentiation; as RNA-binding proteins, the nHu proteins may participate in gene regulatory events that are essential for acquisition of the neuronal phenotype.

We have identified a number of candidate mRNA targets of the nHu proteins. Our data suggest that the majority of these mRNAs interact with nHu proteins through sequences present in their 3' untranslated regions (UTRs). From this 3'UTR target subset, several mRNAs were selected for further examination based on reported roles for their encoded proteins during axonogenesis, a critical developmental process during which nascent neurons grow and extend axons that eventually connect to and form synaptic connections with other neurons. The mRNAs chosen encode for cytoskeleton-modifying proteins; Cofilin, Vasodilator-Stimulated Phosphoprotein (VASP) and the Rho GTPase Cdc42.

The primary aim of the work reported in this thesis was to characterise the effect of interactions between the neuronal Hu protein HuC, and the CLIP-identified 3'UTRs listed above. To do this, the 3'UTR sequences were cloned into reporter vectors (both fluorescent and luciferase reporter-based) to produce reporter protein-encoding messages that included a putative target 3'UTR. These vectors were then used in co-transfection experiments with or without HuC and measurements of reporter protein and mRNA abundance obtained. Interestingly, despite initial speculation that HuC might be involved in directly regulating protein expression from target mRNAs, no significant effect of HuC on protein production from any of the 3'UTR-reporter mRNAs tested was observed. However and quite unexpectedly, measurement of 3'UTR-reporter mRNA abundance from co-

transfection assays revealed a potential role for HuC in modulating alternative polyadenylation site choice for one of the CLIP-identified 3'UTR sequences. Regulation of mRNA polyadenylation site choice may be a novel mechanism by which nHu proteins post-transcriptionally control gene expression during neuronal development.

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Thesis abstract

Progressing business model research towards mid-range theory building

Susan Christine Lambert

Abstract of a thesis for a Doctorate of Philosophy submitted to the University of South Australia, Adelaide

The concept of a business model became prominent during the dot-com boom of the 1990s from which time scholarly research in both electronic commerce and in mainstream management and information systems burgeoned. The driving force behind much of the scholarly activity is the need for enterprise leaders to understand how their existing businesses can adapt and thrive in the marketplaces that have been transformed by Internet based commerce. These requirements extend from information systems issues, to marketing, to entrepreneurship and strategic management. Business model research has grown from several perspectives and has resulted in competing conceptualisations of the business model being formed.

In this thesis an overall plan for progressing business model research towards mid-range theories is proposed. The plan is based on a comprehensive analysis of existing business model research and draws on meta-theory from the more mature social and natural sciences. The overriding theme of the thesis is bringing order to the research domain at both a holistic and component level.

At the holistic level a theoretical framework is derived from accounting, management and information systems meta-theory that identifies exiting business model research and reveals gaps in the research. The theoretical framework permits research to be analysed according to the conceptual focus of the research (focus on the concept itself or on the relationships between the concept and some other phenomenon), the purpose and components of the research and, with respect to empirical research, in relation to its direction of reasoning. Complementing the theoretical framework is a business model research schema, which is derived from the natural sciences. The business model research schema ties together conceptual and empirical research and recognises the need for both inductive and deductive empirical research. Furthermore the business model research schema promotes the need for generalisations on which to base mid-range theories of business models.

The holistic analysis of existing business model research points to two major requirements; a reference model that serves as a tool to evaluate existing (and to develop new) business model frameworks and a general classification scheme for business models. In order to design a general classification scheme for business models a hierarchically structured, all-purpose business model framework is required.

The reference model guides the development of a hierarchical business model framework which is constructed using the modelling principles of the object-oriented paradigm. The object-oriented paradigm is used in the computer sciences for information systems modelling, design and programming and provides the means by which complex problems can be addressed through hierarchically structured modelling principles and conventions. Taxonomical research is applied to the task of designing a theoretically sound classification scheme for business models.

In summary, the contribution of this thesis is to analyse the existing business model research and to progress the research towards mid-range theory building. This will be achieved through the development of a business model framework reference model, a taxonomically sound, hierarchically structured business model framework and an original classification scheme of business models.

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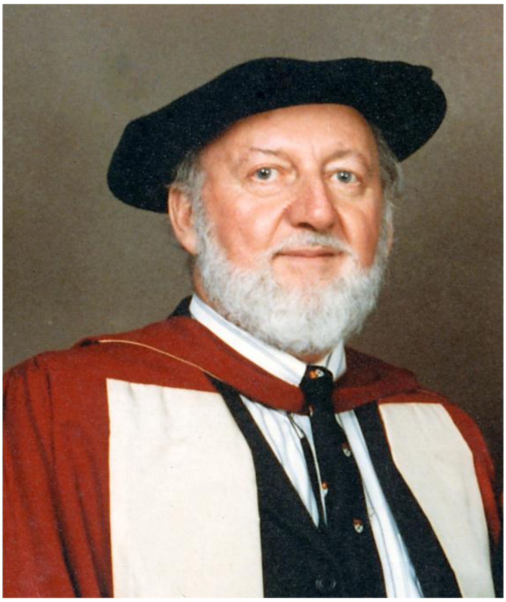
Obituary

Professor Jak (John Charles) Kelly FRSN
(14 February 1928 – 11 February 2012)



Jak (John Charles) Kelly was born in Borenore, a small village about 30 km west of Orange in New South Wales. The son of a contract wheat harvester, he obtained a scholarship to the De La Salle Brothers school in Armidale and progressed to the University of Sydney, where he fell in love with physics and caving. In 1948, Jak became founding President of the Sydney University Speleological Society and became a local caving icon. Opening the 50th SUSS meeting in 1998, he recalled running out of oxygen: "People were unable to strike matches for their cigarettes. It took 45 minutes to get down and 5 minutes to get out!".

Graduating in 1950, Jak worked at the National Standards Laboratory in Sydney, publishing his first paper in *Nature* in 1950 on his invention of vibration measurement using multiple beam interferometry. In 1953, he married Irene Traub, who remained at his side for the next 59 years.

In 1955, Jak moved to the University of Reading to complete a thin-film PhD project under O.S. Heavens. In order to create better quality thin films he invented Electron Bombardment Deposition using a pendant droplet of melted metal heated by an electron beam. This became a standard method of high temperature metal evaporation. Graduating in 1958, he then worked at Harwell Laboratories in Oxfordshire on radiation damage in crystals, grown using his single drop method.

Jak returned to Australia in 1961 to take up a position at the School of Physics at the University of New South Wales, where he remained for the rest of his salaried career, writing more than 150 papers. He specialised in ion beam deposition, patenting several improvements and co-authoring three books. He served as Chair of the Australian Institute of Physics in 1965-66, became a Fellow of the Australian and UK Institutes of Physics, and in 1975 was created a Doctor of Science for his body of work. His curiosity was broad and his subsequent cooperation with other groups involved thermoluminescent dating, using ion implantation to improve the attachment of bone cells to prosthetic surfaces, the modelling and deposition of thin-film solar energy absorbers, irradiation of wool using ion beams to improve wool properties, studying low energy nuclear reactions, and proposing laser fusion improvements.

At UNSW Jak served as Head of School and Science Faculty Chairman (1985-89), and he was Chairman of the Australian Academy of Science Section A and other prominent committees. He retired in 1989, remaining a visiting professor. He became Editor of Australian Physics (1992-98), Honorary Professor of Physics at Sydney University in 2004, President of the Royal Society of NSW (2005 and 2006) and subsequently Editor of its Journal and Proceedings. He was appointed an Inaugural Fellow of the Society in 2009.

Jak was an outstanding ambassador for Physics. His flamboyance, fluency and sense of humour found a ready audience in younger students and drew many into Physics as a career. Many still remember him playing the scientific sage in 1980 in a Robyn Williams ABC Science Show spoof about the discovery of a 60,000 year old fossilised beer can. He supervised many PhD students who became friends and remained so.

Jak died with his family around him, three days before his 84th birthday. He is survived by Irene, who for years assisted the Royal Society in its Sydney office, their daughter and former science broadcaster Karina Kelly, who preceded Jak as President of the Society, and sons Michael and Julian.

David Mills
John Hardie
Heinrich Hora

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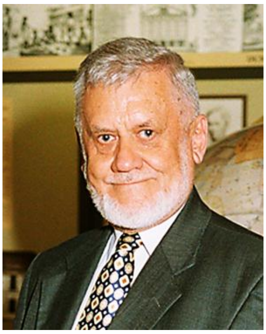
Obituary

Peter J. Tyler

(17 March 1934 – 5 May 2012)



The Society was greatly saddened by the recent death of our historian Dr Peter J. Tyler. He was a great friend and advocate of the Society and made major advances towards our understanding of the Society's contributions to learning and scholarship in NSW.

Peter John Tyler grew up in Singleton in the Hunter Valley and moved to Sydney with his family after World War II. He attended Knox Grammar School and gained his first job with Ku-ring-gai Council. His broad interests soon led him to amateur theatre and a role at the Arts Council of NSW. He became head of the Workers Educational Association, National Secretary of the Australian Institute of Environmental Health, Executive Director of the Building Construction Council of NSW and Chairman of the NSW Construction Industry Training Board. Peter always had a yearning to learn.

In middle age, he gained a Master of Letters and a PhD from the University New England. As a result, he became a noted historical researcher, writing books and papers about medical history, building, anti-tuberculosis campaigns, the NSW public service and the state records of NSW.

Peter became interested in the Society through its historical collection and was selected to work on two Community Heritage Grants we received from the National Library of Australia. Peter was awarded the inaugural Merewether Scholarship by the State Library of NSW and chose as his topic the history of the Society. He found the Society's archives held in the Mitchell Library to be an important source of historical information. This led to him extending his work to writing a complete history of the Society in two volumes. Sadly, this work was left incomplete but the Society intends to engage others to finish Peter's work.

Peter also intended to collaborate on an account of the life of Alexander Berry, one of the members of the Society's first incarnation, the Philosophical Society of Australasia. Peter spoke at Society meetings and had papers published in the Journal and Proceedings. At the time of his death Peter was coordinating the publication of the papers delivered at a seminar held last December on the contributions made by NSW Governor Sir Thomas Brisbane.

Peter will be greatly missed by his mother, his sister, Robin, and his many friends in the Society and other organisations to which he contributed so fully and enthusiastically.

John Hardie
Donald Hector

The Royal Society of New South Wales

Royal Society of NSW Scholarships 2012

The Royal Society of NSW Scholarships are funded by the Society to recognise outstanding achievements by early-career individuals working in a science-related field.

Applications for Royal Society of NSW Scholarships are sought from candidates working in a science-related field in New South Wales or the Australian Capital Territory. Up to three Scholarships will be awarded each year. Applicants must be enrolled as research students at a University in NSW or the ACT, and must be Australian citizens or Permanent Residents of Australia.

The award consists of a certificate acknowledging your achievement, a $500 prize and a free one-year of membership of the Society. The winners will be expected to deliver a short presentation of their work at the Monthly Meeting of the Society on Wednesday 7th December 2011 in Sydney, and prepare a short paper for the Society's Journal.

For further information and inquiries please contact the Society at info@royalsoc.org.au or by telephone on 02 9036 5282.

Applicants should email their submission to: secretary@royalsoc.org.au **by 30th September 2012**.

The Edgeworth David Medal 2012

The Edgeworth David Medal, established in memory of Professor Sir Tannatt William Edgeworth David, FRS, a past President of the Society, is awarded for distinguished contributions by a young scientist.

The conditions of the award of the Medal are:

- The recipient must be under the age of thirty-five years at 1st January, 2012.
- The Medal will awarded be for work done mainly in Australia or its Territories or contributing to the advancement of Australian science.

Nominations are called for the names of suitable persons who have contributed significantly to science, especially the scientific aspects of agriculture, engineering, dentistry, medicine and veterinary science.

Agreement of the nominee must be obtained by the nominator before submission and included with the nomination.

The winner will be expected to write a review paper of their work for submission to the Society's Journal and Proceedings.

Only electronic submissions will be accepted. Nominations and supporting material must be submitted to the Honorary Secretary at secretary@royalsoc.org.au no later than **30th September 2012**.

The winner will be announced and the Medal presented at the Annual Dinner of the Royal Society of NSW to be held in 2013.

The Clarke Medal 2012

The Clarke Medal was established to acknowledge the contribution by the Rev William Branwhite Clarke MA FRS FGS, Vice-President of the Royal Society of New South Wales from 1866 to 1878 The Medal is awarded annually for distinguished work in a natural science done in Australia and its Territories.

The Medal is awarded by rotation in the fields of geology, botany and zoology. This year's award is in the field of Zoology in all its aspects, and nominations are called for the names of suitable persons who have contributed significantly to this science.

Nominations should include a list of publications, a full curriculum vitae and a statement clearly indicating which part of the nominee's work was done in Australia and which part was done overseas.

The winner will be expected to write a review paper of their work for submission to the Society's Journal and Proceedings.

In cases where the Council of the Society is unable to distinguish between two persons of equal merit, preference will be given to a Member of the Society.

Agreement of the nominee must be obtained by the nominator before submission and included with the nomination.

Nominations and supporting material should be submitted to the Royal Society of New South Wales.

Only electronic entries will be accepted and must be submitted via e-mail to the Society at this address secretary@royalsoc.org.au, marked to the attention of the Honorary Secretary not later than **30th September 2012**.

The winner will be announced and the Medal presented at the Annual Dinner of the Royal Society scheduled to be held in 2013. The winner will be notified at least two weeks beforehand.

The James Cook Medal

The Cook Medal was established in 1947 with funding by Henry Ferdinand Halloran. Halloran, who had joined the Society in 1892 as a 23 year-old, was a surveyor, engineer and town planner. He did not publish anything in the Society's Journal but he was a very enthusiastic supporter of research. Halloran funded what were to become the Society's two most prestigious awards, the James Cook Medal, and the Edgeworth David Medal, the latter the medal for young scientists.

The James Cook Medal is awarded at intervals for outstanding contributions to science and human welfare in and for the Southern Hemisphere.

Agreement of the nominee must be obtained by the nominator before submission and included with the nomination.

The winner will be expected to write a review paper of their work for submission to the Society's Journal and Proceedings.

Only electronic submissions will be accepted. Nominations and supporting material must be submitted to the Honorary Secretary at secretary@royalsoc.org.au no later than **30th September 2012**.

The winner will be announced and the Medal presented at the Annual Dinner of the Royal Society of NSW to be held in 2013.

The Royal Society of New South Wales

The Warren Prize

The Warren Prize has been established by the Royal Society of NSW to acknowledge Professor William Henry Warren's contribution both to the Society and to the technological disciplines in Australia and internationally. In 1884, Professor Warren established the first engineering faculty in New South Wales at the University of Sydney and was appointed as its Professor. He was President of the Royal Society of New South Wales on two occasions. He had a long career of more than 40 years and during this time was considered to be the most eminent engineer in Australia. When the Institution of Engineers, Australia was established in 1919, Professor Warren was elected as its first President. He established an internationally respected reputation for the Faculty of Engineering at the University of Sydney and published extensively, with many of his papers being published in the *Journal and Proceedings of the Royal Society of New South Wales*.

The aim of the prize is to recognise research of national or international significance by engineers and technologists in their first two decades or so of professional practice. The research must have originated or have been carried out principally in New South Wales. The prize is $500.

Entries are by submission of an original paper written to academic standards. The paper should review the research done and identify its national or international significance. Preference will be given to entries that demonstrate relevance across the spectrum of knowledge – science, art, literature and philosophy – that the Society promotes.

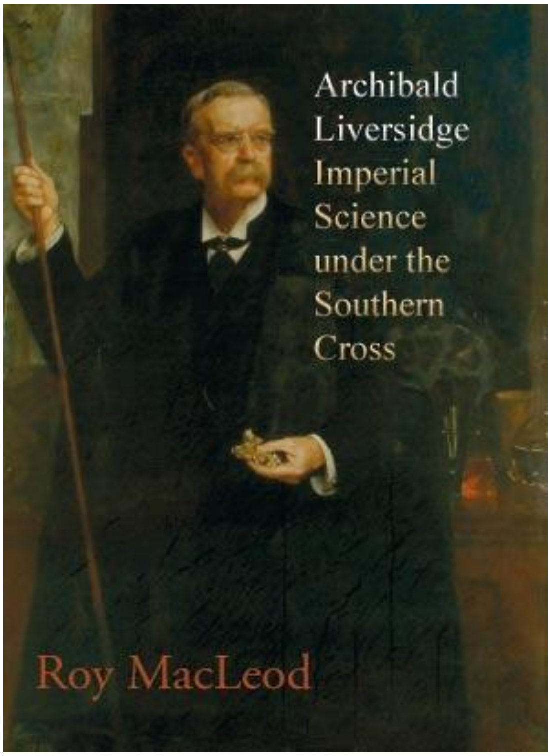
Only electronic submissions will be accepted. Papers may be submitted via e-mail to the Society at this address: editor@royalsoc.org.au. Entrants are referred to "Information for Authors" available from the Society's web-site.
(http://www.royalsoc.org.au/publications/author_info.html).

Entries for the 2012 award close on **31 October 2012**.

The winner will be announced and the Prize presented at the Annual Dinner of the Royal Society of NSW to be held in 2013.

Archibald Liversidge: Imperial Science under the Southern Cross

Roy MacLeod
Royal Society of New South Wales, in association with Sydney University Press
ISBN 9781-9208-9880-9



When Archibald Liversidge first arrived at the University of Sydney in 1872 as Reader in Geology and Assistant in the Laboratory, he had about ten students and two rooms in the main building. In 1874, he became Professor of Geology And Mineralogy and by 1879 he had persuaded the University Senate to open a Faculty of Science. He became its first Dean in 1882.

In 1880, he visited Europe as a trustee of the Australian Museum and his report helped to establish the Industrial, Technological and Sanitary Museum which formed the basis of the present Powerhouse Museum's collection. Liversidge also played a major role in establishing the *Australasian Association for the Advancement of Science* which held its first congress in 1888.

This book is essential reading for those interested in the development of science in colonial Australia, particularly the fields of crystallography, mineral chemistry, chemical geology and strategic minerals policy.

To order your copy, please complete the form Liversidge Book Order Form available at: http://royalsoc.org.au/books and return it together with your payment to:

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Manuscripts are only accepted in digital format and should be e-mailed to: editor@royalsoc.org.au

If the file-size is too large to email it should be placed on a CD-ROM or other digital media and posted to:

The Honorary Secretary (Editorial),
The Royal Society of New South Wales,
121 Darlington Road,
DARLINGTON NSW 2006.

Manuscripts will be reviewed by the Editor, in consultation with the Editorial Board, to decide whether the paper will be considered for publication in the Journal. Manuscripts are subjected to peer review by at least one independent reviewer. In the event of initial rejection, manuscripts may be sent to other reviewers.

Papers (other than those specially invited by the Editorial Board) will only be considered if the content is either substantially new material that has not been published previously, or is a review of a major research programme. In the case of papers presenting new research, the author must certify that the material has not been submitted concurrently elsewhere nor is likely to be published elsewhere in substantially the same form. In the case of papers reviewing a major research programme, the author must certify that the material has not been published substantially in the same form elsewhere and that permission for the Society to publish has been granted by all copyright holders. Letters to the Editor and short notes may also be submitted for publication.

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