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# Quasars and Radio Galaxies

RAGBIR BHATHAL

**Abstract**

Richard Hunstead is one of thirty-three Australian Science Citation Laureates whose papers have been most frequently cited by other scientists around the world. His discovery of variability in radio sources of low frequencies generated a large number of related research projects internationally. He also conducted a seminal study of the evolution of the so-called Lyman alpha absorption forest in distant quasars in the mid-1980s, pioneering observations of quasar absorption lines at high spectral resolution and measurement of the heavy-element enrichment of galaxies at high redshift. He has been leading an international team to find the first massive galaxies to form. This study will provide insights into the formation of galaxies in the early universe.

**Keywords:** Quasars, Radio galaxies, Early universe

## INTRODUCTION

He could have become a professional musician if he had wanted to be one but instead chose to become an astronomer to observe and probe the secrets of the music of the universe. His mother, Dagmar Roberts was a well known concert pianist and a child prodigy who began learning the piano at the age of three and won her first competition at the Drummoyne Eisteddfod five years later. In fact, at ninety-five years of age she may be the oldest student of the Sydney Conservatorium of Music. So the genes of music were already in him. 'I was quite good at the piano and competed successfully in Eisteddfods and on one occasion played on the radio in one of the children's programs.' At school he used to conduct 'the school choir and I actually composed a Christmas carol and conducted it when I was in my sixth class.' He had even been selected to play at the end of the year concert at Sydney Town Hall but according to him, 'unfortunately that never happened because I developed pneumonia and my substitute was Roger Woodward who went on to a career overseas and he is now back here as a teacher in Australia.'

## INTEREST IN ASTRONOMY

In addition to his interest in music he was also interested in things mechanical. 'I liked to dismantle things and put them back together. I was interested in science but more in chemistry than in physics at high school.' He attended government schools. In fact, he attended a selective school (North Sydney Boys High School) for his secondary education which according to him had teachers who were 'genuinely interested in students.' At school he was also interested in photography and in order to process his photographs he converted the laundry at home in Turramurra into a darkroom. The skills he acquired in mucking around with things scientific and technical as a young boy were to come in handy when he went on to become an astronomer. His interest in astronomy came much 'later in high school' and crystallised at university when he came under the influence of Bernard Mills, the inventor of the Mills Cross and an extremely innovative radio astronomer (Mills 2006). 'While at high school', he said, 'he was aware of the growing field of radio astronomy that was getting a fair bit of publicity in the newspapers.' This was in the late 1950s when astronomers like Bernard Mills, Joseph Pawsey and Chris Christiansen were carving out a niche for Australia in the international world of astronomy (Bhathal 1996). He was about fifteen years old at that time.

## SYDNEY UNIVERSITY

He went up to Sydney University for his undergraduate and postgraduate studies and surprisingly 'never left the place.' 'Although he was', he said, 'near the top of the class for most of the time at North Sydney Boys High School', in his first year at university he found that there were 'lots of other very bright people'. He found this daunting particularly when he was exposed in 'my first lecture to Harry Messel. That sort of blew me away.' Messel, according to Hunstead, 'came across as a God-like figure, who had a booming voice and I perceived him to have very little tolerance for people who didn't understand what he was saying.' Messel was the Head of the School of Physics and was responsible for setting up the very successful Science Foundation for Physics. He was an extremely energetic and enthusiastic person who managed to persuade the captains of industry 'into contributing vast sums of money to the Foundation.' One of his great legacies was the creation of research groups and professorships in the School of Physics (Millar 1987). He persuaded Bernard Mills and Hanbury Brown to join the School of Physics. Both Mills and Hanbury Brown were extremely productive and innovative astronomers with international reputations.

For his honours year, Hunstead worked with Mills' radio astronomy group and did 'some work which ultimately was used in the construction of the Mills Cross telescope.' 'It was a way of steering the north-south arm of the telescope to minimize the amount of switching of delay lines that was necessary to steer it from the north horizon to the south horizon of the telescope. In those days a punch card was used to actually steer the telescope.'

After completing his honours in 1963 he went on to do his PhD under the supervision of Mills. His task was 'to look after the pointing calibration of the telescope. That is, how accurately could we determine the positions of the radio sources because our ultimate aim was to catalogue all of the strong radio sources. That was the principal driver for the Molonglo Cross telescope which operated at 408 Megahertz.' The Molonglo Cross telescope was built 30 kilometres east of Canberra near the township of Bungendore. He had to make frequent trips to collect data. He began during his PhD work to set about measuring the optical positions for a large number of counterparts of radio sources. According to him, 'this technique had not been used before on the Palomar Sky Survey plates and it was quite a pioneering study which made me somewhat notorious amongst traditional astronomers.' For carrying out his measurements he used a X-Y measuring machine which was designed by the CSIRO's National Measurement Laboratory and built in the School of Physics to very high technical standards. Apart from collecting the data on chart recorders it was also collected digitally. According to Hunstead, 'it was amongst the first digitally recorded data at a radio telescope.'

Before completing his PhD thesis he had already published eight papers in international journals. One paper in particular on the optical variable PKS 1514-24 was rather interesting (Hunstead 1971). It belonged to the category of BL Lac objects. It was the second known object in this class that he had discovered. It turned out not to be a star but a galaxy which showed enormous variability. He had drawn attention to a close agreement between a variable star called AP Lib and the Parkes radio source 1514-24. 'I had measured both the optical and radio positions for that object', he said. According to him, 'these very rapid variations are associated with the orientation of the radio jets in the case of radio emission and the optical accretion disc in the case of light emission that is more or less beamed directly towards us. Any small changes in direction can make big changes in the intensity of radiation we receive.'

## QUASARS AND GALAXIES

Hunstead has carried out significant work in the fields of quasars and radio galaxies. According to Hunstead, 'quasars are the active cores of galaxies which have at their centres a super massive black hole with a mass of the order of a thousand million times the mass of the Sun which is actively accreting material from ripped up remnants of stars. The radio emission that we see is due to the very high energy particles that are generated in a accretion disc around a black hole'. 'The optical emission,' he continued, 'on the other hand is coming from the accretion disc itself which is at a temperature of around 10 million degrees in these objects, which means it emits at wavelengths in the soft X-ray to extreme ultraviolet.'

While trying to establish the flux density calibration of the Molonglo telescope he found four variable radio sources at 408 Megahertz. He discovered that they shared something in common, viz: they were all identified optically with quasars. He saw these large variations at 408 Megahertz and 'didn't know what to make of this.' Astronomers at Arecibo and Jodrell Bank had also found some anomalies in their data but 'had thought nothing of it', he said. He published a paper in 1972 (Hunstead 1972) to show that 'the variations that we were seeing at 408 Megahertz didn't match at all with what we were seeing at high frequency' The paper not only triggered a lot of interest but also generated a number of PhD projects and observations at low frequency telescopes. 'All the low frequency telescopes around the world started looking at radio sources for variability. And a number of people that I've met subsequently have blamed me for giving them a PhD project which was to measure lots and lots of flux densities of radio sources. One of them was Jim Condon. Another one was Bill Cotton who works at the VLA.' Ten years later after his discovery a workshop was held on the topic (Cotton & Spangler 1982).

Three years later he wrote a paper on 3C 411, a newly discovered N galaxy with a large redshift (Spinrad, et al. 1975). At that time the connection between radio galaxies and quasars had not been agreed on. 'So there was a lot of interest' Hunstead said, 'in actually obtaining a complete set of redshifts for all of the galaxies in the 3rd Cambridge Catalogue.' The work was carried out as a collaborative effort between three institutions. Martin Ryle from Cambridge University did the radio observations while Hyron Spinrad from the University of California at Berkeley used the Lick telescope to carry out the spectroscopy measurements and Hunstead did the optical position measurements with his X-Y measuring machine. A Nobel Prize was awarded to Ryle a year later for his development of synthesis imaging.

One of the other ways of resolving the issue of whether there was a connection between radio galaxies and quasars was according to Hunstead, 'to find chance alignments between a background quasar and a foreground galaxy, in which you could then look at the spectrum and show that it was actually behind the galaxy.' From their observations of very weak calcium lines in the spectrum of QSO 0446-208 they were able to ascertain that the absorption was due to an intervening galaxy (Blades, et al. 1981). It was only the second example of such absorption that had been observed. The study of absorption lines allowed them to probe distant galaxies and as a result of this 'we were able to learn something about heavy elements that were present in those galaxies and it acted as a launching pad for our subsequent work in looking at element abundances in galaxies that happened to lie along the sight lines to distant quasars.'

His studies on QSO 2000-330 at $z = 3.78$ (Murdoch, et al. 1986) led to a reappraisal of much of the earlier work on quasars. There were claims that the number of absorption lines increased with redshift while others claimed that the numbers decreased or there was no change with redshift. His team was 'able to measure the density of Lyman-alpha lines in a very controlled way in this high redshift quasar at a redshift of 3.78, which was then the highest redshift quasar known, combined with the lowest redshift object, BL Lac object 0215+015. They gave us the lever arm that enabled us to determine the abundance or the density of these Lyman-alpha absorption lines unequivocally.' They used the 'maximum likelihood technique' to good effect. The technique is now 'used universally for exploring this process of evolution with redshift.'

In the process they also discovered something interesting. According to Hunstead, 'We discovered that the reason for the earlier discordant results was because the quasar itself was influencing its local environment and that the region around the quasar was being ionised by the quasar so that there were fewer clouds of neutral hydrogen around the quasar, so the number of absorption lines diminished as you went towards the quasar. But if you looked away from there you indeed saw a very prominent increase with redshift.'

In the 1980s there was a realization amongst astronomers that there was a class of absorbers that could be seen against distant quasars. The column density of neutral hydrogen was so large that it actually blocked out the light of the quasar altogether over a range of wavelengths. By determining the hydrogen column density accurately it is possible to measure the strength of heavy element lines that are associated with that hydrogen. In this way one can make an abundance measurement. Abundance measurements are always made of the ratio of the element of interest to hydrogen. He chose two elements (zinc and chromium) to make abundance measurements. According to Hunstead, 'most of the elements that are produced in stars don't stay in the gas phase in the inter-stellar medium. They get attached to grains of dust and are basically depleted from the gas phase. So by measuring the gas phase abundance of an element like iron you're getting a very misleading impression of how much iron there is out there.' 'It turns out that one element, zinc', he continued, 'is hardly ever depleted on to dust grains and the abundance of zinc in different sight lines within the Milky Way galaxy towards hot clouds and cool clouds is more or less the same. And so zinc was not depleted on to dust grains. We don't understand why because the nucleosynthetic origin of zinc and iron are very similar. Zinc could then be used as a tracer of the heavier abundance at high redshift when it was used in conjunction with the Lyman-alpha line. It also happens that close to the zinc lines are chromium lines. Now chromium like iron is very heavily depleted on to dust and so by measuring the relevant abundances of both zinc and chromium you could determine the abundance of the heavy elements using the zinc abundance and you could learn how much dust there was by looking at the chromium abundance or the chromium to zinc ratio. (Pettini, et al. 1994)'.

Most astronomers had assumed that all quasar spectra were the same. That is, the spectrum obtained for a radio loud object and a radio quiet object looked very much the same. However, no one had actually generated composite spectra to study the question. Hunstead and Joanne Baker who had come down from Cambridge University to do her PhD discovered that 'the radio spectra were quite different depending on whether you had a quasar pointing towards you or with its jets in the plane of the sky. And all of them were different from another class of quasars called compact steep spectrum quasars and they in turn were different from the optically selected quasars.' This was the first example where a distinction was drawn between the radio loud and radio quiet objects (Baker & Hunstead 1995).

He is now leading an international team which is investigating how the first massive galaxies formed. This is a follow up, he said, 'of the work he had done on quasars.' One of the important features of quasar astronomy is that most of the light that is seen is coming from a very active nucleus which overwhelms the light from the host galaxy. According to Hunstead, 'In order to learn more about galaxy formation in the early universe you need to find radio galaxies where the light from this very bright nucleus is not pointing towards you but is pointing in the plane of the sky. It may be illuminating clouds laterally but not along the line of sight. So then you actually explore the building up of massive galaxies at early times because both quasars, radio loud quasars and radio galaxies have the same hosts basically, these giant elliptical galaxies.' For this project his team has to use various astronomy facilities such as the Molonglo Synthesis Telescope, the VLA, the Anglo-Australian Telescope, the European Southern Observatory and the eight metre Gemini telescope.

## POSTGRADUATE STUDENTS

He has over the years supervised a number of PhD students who have gone on to lead productive astronomical careers. Some of these include John Reynolds who is currently the Director of the Parkes Radio Telescope, Vickki Meadows who is now at Caltech and is closely associated with the Spitzer telescope, Joanne Baker went on to a post-doctoral fellowship at Cambridge University then won a Hubble Fellowship at Berkeley and is now Chief Editor in the UK for the planetary science section for Science magazine, Tanya Hill is the science communicator at the Melbourne Planetarium and Melanie Johnson-Hollett is a lecturer at the University of Tasmania.

Hunstead has a track record of highly cited publications and was recently recognised by being awarded the Australian Science Citation Laureate. His productivity he says is due to the fact that 'I am working on many projects. It has meant that I never become an expert in any one field but I have become a semi-expert in a whole lot of fields. That enables you to make connections between fields that you would not otherwise be able to do.' He works long hours. 'I usually come to work on Saturdays as well and sometimes on Sundays.'

As to his major achievements to date he said, 'I don't place a lot on the research that I've done, although I've enjoyed it. It's all been great fun. I get the biggest buzz from working with students and seeing them develop into researchers through to their PhDs and beyond.'

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Ragbir Bhathal
OZ OSETI Project, School of Engineering,
University of Western Sydney,
Locked Bag 1797, Penrith South DC, NSW 1797
email: R.Bhathal@uws.edu.au

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