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THE UNBEARABLE WHITENESS OF BLACK HOLES

How in 1963 a Dutch-American astronomer discovered "quasars" whose prodigious luminosity could be explained only by matter heated to incandescence as it swirls down onto a "supermassive" black hole

"Twinkle, twinkle quasi-star
Biggest puzzle from afar
How unlike the other ones
Brighter than a billion suns
Twinkle, twinkle, quasi-star
How I wonder what you are."

George Gamow[1]

"Supermassive black holes give out no light and yet are the brightest objects in the universe"

Kip Thorne[2]

PASADENA, TUESDAY 5 FEBRUARY 1963

For almost six weeks the spectrum had sat among several others on his desk, but he had looked at it only intermittently because it made absolutely no sense. On returning to his office after a light lunch at Caltech's Athenaeum, Maarten Schmidt squinted at the spectrum through his desktop viewer. No. He shook his head. It still made no sense.

The spectrum had been obtained with the 5-metre Hale Telescope on Mount Palomar, 65 kilometres north of San Diego. On the night of 29 December 1962, he had taken the elevator to the prime focus cage, a two-metre-diameter barrel built into the telescope's steel skeleton and suspended a dizzy 15 metres above the giant parabolic mirror. It was there that the light collected by the "Big Eye", the largest telescope in the world, was focused and concentrated. And it was there that was located the "spectrograph", which fanned out the light into its constituent colours just like a glass prism.

Schmidt's target was of a curious star which coincided with 3C 273: the 273rd object discovered by the Third Cambridge Survey of Radio Sources (3C), published in 1959. His challenge was to keep the pinpoint of light from 3C 273 hovering on the slit of the spectrograph, a task which involved nudging the telescope continually with the up-and-down and side-to-side buttons of a hand control. It was freezing in the cramped cage but, inside his "Army Air Forces" suit, an electrically heated relic of the Second World War, he was warm and snug. His only concern was for his bladder since, the moment the elevator moved out of the way so that observations could begin, he would be marooned for eight straight hours with no possibility of a toilet break.

Schmidt had actually obtained a spectrum of 3C 273 two nights earlier, but it was a disaster. He had taken it towards the end of a night's observing when the Sun was threatening to come up and he was looking forward to going to bed. The moment he extracted the plate from the spectrograph and examined it with a dim red torch light, it was clear it was badly overexposed.[3] His excuse was that he had never before observed anything so bright. The "magnitude" of 3C 273 was 12.9, making it as brilliant as stars in our own galaxy, whereas his usual quarry was very distant and very faint nineteenth magnitude galaxies, more than 200 times fainter.* So feebly did their light rain down from the night sky that it often took hours to collect enough in the giant light bucket of the 5-metre telescope to create a discernible spectrum. It did not help that photographic plates were so insensitive that they threw away 98 per cent of the incident light.

Before the night's observing run, Schmidt had carefully prepared glass spectrum plates in the Palomar dark room. Each was one inch long and a third of an inch wide, and cut from a standard five-by-seven-inch photographic plate. He had then

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* A celestial object with an "apparent magnitude" five times larger than another is 100 times fainter. The faintest star visible to the naked eye has a magnitude of about 6 while the apparent magnitudes of the full Moon and the Sun are -12.7 and -26.7, respectively. This means the Sun shines about a million times brighter than the full Moon.

transported them to the prime focus cage in a light-tight container about the size of a cigar box.[4] Taking his gloves off, he selected a new one and carefully inserted it into the spectrograph. He waited, patiently. The music of Bach and Telemann played over the dome's sound system as an unbroken veil of stars sailed overhead. He could think of no more romantic profession than that of an astronomer. As a member of the staff of the Hale Observatory, he was entitled to twenty to twenty-five nights a year of observing on the Big Eye. Occasionally, he had to pinch himself to prove he was really there. How had a little boy who had cowered under a kitchen table as Groningen burned, fearing he might not see the morning, end up at the prime focus cage of the most powerful telescope in history as it probed the farthest reaches of the cosmos?

After an exposure of fifteen minutes, he extracted a spectrum of 3C 273. It was perfect. It was the very same one he was now inspecting through the viewer on his desk.

What had prompted him to take a fresh look at the spectrum today was a letter from a former Caltech colleague, now in Australia. John Bolton wrote that Cyril Hazard, a member of his team at the Parkes Observatory in New South Wales, was submitting a paper on the location of 3C 273 to the journal *Nature*. Would he write a companion paper on the object's spectrum? Schmidt had the greatest respect for Bolton as a fellow tenacious observer – though of the radio rather than visible universe – so he was more than happy to oblige. His concern, however, was that there was very little he could say on the subject of 3C 273 apart from: "Here is a spectrum. It is utterly baffling."

He sat back in his chair for a moment and rubbed his eyes. A small group of "techers" were passing the Robinson Laboratory of Astrophysics, their books under their arms. Even after almost a decade in Southern California, he still marvelled at the sight of students in tee-shirts and shorts in mid-winter. Though it was cloudy in Pasadena today, it was a balmy 20 degrees and he didn't even need to put on a jacket to stroll along the Olive Walk to the Athenaeum.

Snapping himself out of his reverie, Schmidt flicked through his observer's notebook for 29 December 1962 and found the page on which he had recorded in small, neat pencil the details of the spectrum of 3C 273: date, time, exposure length, and so on. Typically, a stellar spectrum was crossed by spidery black lines, which were caused by the absorption of light by atoms in a star's cool outer regions. Very conveniently for astronomers, nature had given each kind of atom a characteristic fingerprint of such "spectral lines", so it is possible to recognise the presence of atoms of each element, from hydrogen to calcium to uranium. This flew in the face of the pronouncement in 1835 of the French philosopher Auguste Comte: "Never, by any means shall we be able to study the chemical composition or mineralogical structure of the stars."[5]

Schmidt ran his finger down the page to where he had written the wavelengths of three mysterious spectral lines in 3C 273. He had added a fourth line, recorded the month before in the invisible-to-the-naked-eye "infrared". It had been detected by his Canadian colleague, John Beverley "Bev" Oke, using the 2.5-metre Hooker Telescope on Mount Wilson, above Pasadena, the same instrument used by Edwin Hubble in 1929 to discover the expanding universe. Over the past six weeks, he had asked pretty much every one of his Caltech colleagues if they could identify the four peculiar spectral lines, none of which corresponded to any known element, but none were able to do so. Now that Schmidt was taking a fresh look at the spectrum, it struck him that there was a pattern in the lines he had not noticed before. As they marched towards shorter wavelengths – from red light to blue – they seemed to get ever fainter and closer together.

An idea occurred to him. Why not compare the pattern he was looking at with a known pattern of spectral lines? If there were any similarities, it might at least give him a clue about the identity of the mysterious lines. It was a long shot. But, after six weeks of making absolutely no progress in identifying the lines, he could think of nothing better to try. One thing was for sure. If he did not find something extra to add to his *Nature* paper, it would be embarrassingly short.

As Schmidt pulled his mechanical calculator towards him, another group of students were passing beneath his window. It made him smile to see them tossing a brown-and-white oval American football back and forth between them. Though renowned for their scientific prowess, Caltech students were famed throughout the state for their appallingly bad record in college sports.

For his comparison pattern, Schmidt chose a well-known spectral sequence. The "Balmer series" of hydrogen arises when the single electron in the lightest atom drops to the second highest energy orbit. It can do that from the third highest level, the fourth, the fifth, and so on, and in each case the electron sheds its excess energy in the form of light of a characteristic wavelength.* Schmidt spent his life measuring astronomical spectra so he knew the wavelengths of the common Balmer lines by heart.

Consulting his observer's notebook, he tapped in the

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* The spectral lines created when an electron drops to the first, or lowest, energy level are not visible the naked eye. These "Lyman" lines are in the ultraviolet.

wavelengths of the first spectral line of 3C 273 and, cranking his calculator, divided it by the wavelength of the nearest Balmer line. The ratio came out as 1.16. Next, he divided the wavelength of second line by the wavelength of the nearest Balmer line. The ratio was 1.16. He repeated the process with third line. It was 1.16. And the fourth: 1.16.[6] He shook his head in amazement. There was no doubt about it. What he was looking at was the Balmer series shifted by 16 per cent.

Actually, there were two other lines in the spectrum of 3C 273, one in the red and one at the blue end of the spectrum. Schmidt had left them out because they appeared unrelated to the other four lines. Now, suddenly, he realised they made total sense if they were familiar spectral lines that had been shifted in wavelength by 16 per cent: one due to magnesium that had lost two electrons, and the other to oxygen that had lost three electrons.

Schmidt had chosen the Balmer series as a convenient comparison because it was a well-known series and because its lines were close in wavelength to those in 3C 273. Never for one moment had he believed that the mysterious features might actually be Balmer lines. Such features are simply not found in the spectrum of stars and he was absolutely sure 3C 273 was a star. A weird star, admittedly, but a star, nonetheless.

The frequency of light is like the pitch of a sound. And, just as the pitch of a police siren gets higher as it approaches and lower as it recedes, so does the frequency of light. If the source of the light is approaching, its spectral lines are shifted towards the higher frequency, blue, end of the spectrum, causing a "blue shift". And, if the source is receding, the lines are shifted towards the lower frequency, red, end, creating a "red shift". High-frequency corresponds to short-wavelength and low-frequency to long wavelength. 3C 273's red shift of 16 per cent meant it was hurtling away from Earth at an incredible 16 per cent the speed of light. At such a speed – 47,400 kilometres a second – it would be possible to fly to the Moon in eight and a half seconds. No star had ever been discovered that was speeding through space anywhere near as fast. The only celestial bodies with red shifts as large were galaxies.

Hubble's deduction that the universe was expanding had come from observing that its constituent galaxies – great islands of stars of which our Milky Way is but one – are flying apart from each other like pieces of cosmic shrapnel. The further away a galaxy, the faster cosmic expansion is carrying it away from us. And the further away a galaxy, the longer its light has spent travelling to Earth, and the greater cosmic expansion has stretched its constituent wavelengths, imprinting on its spectrum a "cosmological red shift".

Galaxies, however, appear as fuzzy blobs in telescopes. Their constituent stars are smeared together by sheer distance. None appear as super-bright pinpricks of light. That was why Schmidt was convinced that 3C 273 was a nearby star. But, even for a galaxy, the red shift of 3C 273 was huge. Only one – 3C 29 – was known with a greater red shift. It had been found by Schmidt's colleague, Rudolph Minkowski, who was part of a Caltech team attempting to find optical counterparts of the 3C radio sources.

Given that the further away a galaxy from is us the faster cosmic expansion is carrying it away, its speed of recession yields its distance. The speed of 3C 273 implied it was at least 2.4 billion light years away. It was a thousand times more distant than Andromeda, the nearest big galaxy to the Milky Way. But how could it possibly be so bright in the night sky when it was so far away? Schmidt knew there was only one answer: if it was pumping out dramatically more light than a galaxy of stars. At this realisation, Schmidt jumped to his feet. He had to tell someone.

Out the corridor, Schmidt immediately bumped into Jesse Greenstein. "Jesse! Quick! Come in! There's something I need to show you!" Greenstein, the New Yorker who headed Caltech's astronomy department was taken aback. The tall, gangly Dutchman he had hired four years earlier because of his uncanny ability to eke out every last ounce of performance from the Palomar 5-metre was renowned for being calm and soft-spoken. Greenstein had never before seen him this flushed and animated.

When he had recovered from hearing Schmidt's news, Greenstein immediately said: "We should look at 3C 48!" Like 3C 273, it had unidentifiable spectral lines. The optical counterpart to the radio source 3C 48 had been discovered by Palomar observer Allan Sandage in 1960. The sixteenth magnitude star-like object fluctuated in brightness over a period of only a few months, which had implications for the size of the source. A body that varies its brightness in only a few months must be less than a few light months across because that is the minimum time for a disturbance, travelling at the cosmic speed limit of the velocity of light, to cross the body and so cause all parts of it to brighten or fade in unison. Even the Sun and the nearest star, Alpha Centauri, are separated by 4.3 light years. At light months across, 3C 48 must be far smaller than this separation. It was this, and the fact that it looked like a star, that had convinced Greenstein that it was a star.

It would have to be a very exotic kind of star. Normal stars do not emit much in the way of radio waves yet 3C 48 had popped up in a survey of intense cosmic radio-emitters. Greenstein's best guess was that it was some weird kind of super-compact star relatively nearby in our galaxy. In fact, in

1961, in the Caltech house magazine, *Engineering and Science*, he had written an article on 3C 48 with the title "First True Radio Star?".

Only the week before, Greenstein had come by Schmidt's office with the thick manuscript of a paper he had written on 3C 48. Deeply frustrated that he was unable to include any explanation of its spectrum, he had thrown the paper down on Schmidt's desk, saying: "If you don't have any remarks within a week, I'm going to send it off for publication." Schmidt now retrieved the manuscript from near the top of his in-tray and handed it to Greenstein, who quickly found the page with the spectrum of 3C 48. "The only true voyage of discovery," wrote the French novelist Marcel Proust, "consists not in seeing new landscapes but in having new eyes." With their new eyes, Schmidt and Greenstein saw immediately that the three mystery lines in the spectrum of 3C 48 were also Balmer lines of hydrogen. But not shifted by a mere 16 per cent, as in 3C 273, but by 37 per cent. 3C 48 was hurtling away from us at more than a third the speed of light – a staggering 110,000 kilometres per second. The Hubble expansion put an object with such a recession velocity at a remarkable distance of 5.1 billion light years. There was no way that that 3C 48 could be a mere star.

Oke, having heard the commotion in Schmidt's office, came in to investigate. He was the instrument builder whose supersensitive spectrographs boosted the effectiveness of the 5-metre Mount Palomar and 2.3-metre Mount Wilson telescopes. By now, Schmidt and Greenstein had realised that the spectral line due to doubly ionised magnesium was in the spectrum of both 3C 273 and 3C 48. That was too much of a coincidence. It confirmed to them that they were dealing with the same kind of object.

Over the next couple of hours, the enormity of Schmidt's discovery gradually dawned on the trio. Both 3C 273 and 3C 48 were bright. Not exactly visible to the naked eye but not that far off. To simultaneously appear so brilliant and so extraordinarily far away, they must be enormously luminous – perhaps 100 times more luminous than a normal galaxy. And 3C 273, because it fluctuated on short timescales, must be extraordinarily tiny. What could be pumping out the light of 100 galaxies from a volume not much larger than the solar system? What the hell were 3C 273 and 3C 48?

Schmidt's journey to making his discovery on 5 February 1963 had not been an easy one. Born in Groningen in 1929, he was only ten when low-flying Messerschmitt heralded the Nazi invasion of Holland in May 1940.[7] Two years later, all able-bodied men between eighteen and forty-five were forced to work for the Germans, often digging defensive ditches, though his father, a government accountant, obtained an exemption. If things were not bad enough for the population, conditions deteriorated yet further in the summer of 1944 when the Allies, in their push to liberate Holland, failed to secure the bridge over the River Rhine at Arnhem. In retaliation for a Dutch train strike aimed at hindering the occupiers, the Nazis dismantled the country's entire railway system, sending the iron back to Germany for the war effort. The lack of transport exacerbated food shortages, causing a famine in which tens of thousands starved to death. For the Schmidt family, the endgame was played out in mid-April 1945 as they cowered all night on their kitchen floor, caught in the crossfire between Canadian and German troops, the sky outside turned blood red by the buildings burning in the heart of Groningen.

During the years of fear and persecution, the only consolation for Schmidt were the walks with his father through the city when air raid blackouts left the night sky above inky black and crowded with stars. His uncle Dik happened to be a keen amateur astronomer, and, in the summer of 1942, Schmidt was allowed to look through a telescope from the upstairs window of his pharmacy in Bussum. It was a life-changing event. Back in Groningen, and despite the shortages, he built a telescope with a big lens cadged from his house-painter grandfather, a cardboard tube from a toilet roll, and a small eyepiece of the kind used by biologists to study flowers.

When the war was over, Schmidt finished high school and went to study physics and mathematics at the University of Groningen. In 1949, at a graduate school in astronomy at the University of Leiden, he became interested in mapping the structure of our Milky Way. This was possible because of a prediction made in 1944 by a Dutchman hiding from the Nazis. Hendrik van der Hulst pointed out that neutral hydrogen atoms floating in interstellar space should be broadcasting radio waves at a wavelength of precisely 21 centimetres.* Unlike the visible light from stars that was blotted out by interstellar dust that hung like a dark curtain across space, radio waves could reach us relatively unhindered from great cosmic distances.

On their retreat, the Germans had left behind 7.5-metre Würzburg dishes, which they had used as part of an anti-aircraft radar system. Schmidt and fellow graduate student, Gart

* In a hydrogen atom, the single electron can either have the same quantum "spin" as the single proton or the opposite spin (naively, the spins can be thought of as either as a clockwise or anticlockwise rotation). The state in which spins are aligned has a very slightly greater energy than that in which they are not aligned. So, if the atom drops from the higher to the lower energy state, the excess energy is shed as "photon". This has a wavelength of 21 centimetres.

Westerhout, used such a dish to measure the Doppler shift in the wavelength of the 21-centimetre line. It enabled them to not only map the distribution of hydrogen gas out in space but also pin down how fast it was moving. Schmidt and his PhD supervisor, Jan Oort, then deduced how the hydrogen was spread throughout the galaxy and become the first people in history to "see" the spiral structure of the Milky Way.

Oort enthused about Schmidt's 21-centimetre observations of the Milky Way in a letter to his friend, Walter Baade, at the Mount Wilson Observatory in Southern California. The endorsement impressed Baade. Oort was one of the most important astronomers of his generation. In 1950, he had deduced, from the orbits of comets, that the solar system is embedded in a giant bee-swarm of trillions of such icy bodies, which would become known as the Oort cloud. Baade offered Schmidt a Carnegie Fellowship at the Mount Wilson Observatory's Santa Barbara Street offices in Pasadena. He jumped at the opportunity.

In 1956, Schmidt drove across the US to California with his wife, Corrie, stopping at major observatories along the way. They spent the next two years in Pasadena but, afterwards, returned to Holland. By now they had two daughters, Elizabeth and Marijke. But Holland's postwar housing shortage made it difficult and expensive to find a house big enough to accommodate the family. Schmidt realised, after six months spent in the austere, not to mention chilly, conditions, that he had made a big mistake in coming home. When he was offered a professorship at the California Institute of Technology (Caltech), it was a no-brainer, and he returned to the US with his family in October 1959.

Caltech had relatively recently entered the field of "radio astronomy". In revealing "all the light we cannot see", the fledgling science, pioneered by the men who had worked on radar during the war, had found mysterious compact sources of cosmic radio "noise".[8] By the time of Schmidt's arrival, radio telescopes had reached the point at which they could pin down the locations of such sources precisely enough that photographic survey plates of the night sky could be scoured for optical counterparts. Some appeared to be galaxies pumping out outrageous quantities of energy. Some, even more bizarrely, appeared to be stars. The only way to figure out what exactly the enigmatic objects were, was to take their spectra, which would reveal key aspects like their composition and temperature. And that was the job Schmidt took on at the Big Eye on Mount Palomar shortly after his arrival back in California.

The story of the mysterious cosmic radio sources actually began three decades earlier when Bell Telephone Laboratories set about testing a new transatlantic radio phone service. Such communications could be degraded by radio interference, or "static", and, in 1931, the task of identifying sources of such interference was given to a twenty-six-year-old engineer called Karl Jansky.

Jansky built a radio "antenna" at Holmdel in New Jersey, one of Bell Lab's many sites. An antenna is anything that converts an electromagnetic wave passing through the air into one traveling down a metal "wave guide" so it can be detected by a "receiver". Jansky's antenna was a box-shaped frame of metal pipes and timber the size of a train carriage. It was mounted on four wheels from a Model T Ford, and, with the aid of a small motor and chain drive, could be moved around a circular rail track to "point" in any direction in the sky. Using the contraption, which became known as the "merry-go-round", Jansky discovered three distinct sources of interference at a wavelength of 14.6 metres. First, there was static from local thunderstorms. Second, there was static from distant thunderstorms. Most mysterious, however, was the third and weakest source: "a steady hiss type static of unknown origin."[9]

The hiss seemed to vary in intensity on a daily basis so Jansky guessed it was associated with the Sun. But, after a while, he discovered that the period of fluctuation was not 24 hours; it was 23 hours 56 minutes. This is the time taken for the Earth to return to the same orientation relative to the stars. This "sidereal day" is four minutes less than the time for the Earth to turn once on its axis because the planet is also orbiting the Sun. The fact that the mysterious static was varying over such a timescale indicated it was coming not from the Sun but from a source beyond the solar system.

Jansky published his findings in a paper under the dull title "Directional studies of atmospherics at high frequencies". However, his two follow-up papers were more exciting: "Radio waves from outside the Solar System" and "Electrical disturbances apparently of extraterrestrial origin". By now, Jansky had determined that the radio signals originated in our Milky Way, the thin disk of our galaxy that bisects the sky on a clear night. [10],[11]. Though diffuse static was coming from the whole of the Milky Way, it was strongest in the constellation of Sagittarius, the location of the galactic centre.*

The Bell publicity department went to town promoting the discovery. In May 1933, the *New York Times* ran a front-page report under the headline "New Radio Waves Traced to Center of Milky Way". There was even a radio station in New York

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* Sagittarius A* would later be identified as a 4.2 million solar mass black hole at the heart of the Milky Way.

that ran a special evening program in which its audience got to listen to the cosmic static picked up by Jansky's merry-go-round and relayed directly to the station. It was broadcast as the "hiss of the universe".

Jansky had singlehandedly created the science of radio astronomy.* But his discovery was either not noticed by astronomers or noticed by them but dismissed as unimportant. And Jansky, being an employee of a commercial company rather than a scientific institute, was moved on to other projects. Nevertheless, his research papers were read by a twenty-two-year-old undergraduate student and radio "ham" in Chicago. Grote Reber was so excited by what he read that he immediately wrote to Bell Labs, begging to be employed to follow up on Jansky's work. When the telephone company turned him down, Reber was disappointed but he was not deterred. He would just have to follow up on Jansky's work himself. He decided to create a whole-sky "map" of cosmic radio noise. The task would involve him inventing the modern radio telescope.

Reber needed to do two things: collect as much of the feeble cosmic radio energy as possible and discern as much detail in the radio sky as feasible. Both requirements led him to design a steerable parabolic dish that collected radio waves like a bucket, concentrating them at a focus, where they were detected by a receiver. He built the dish in 1937 in the backyard of his parents' home in Wheaton, Illinois, much to the astonishment of their neighbours. It took him four months and

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* The discovery of cosmic radio waves was not the only major astronomical discovery made at Bell Labs' Holmdel site. In 1964, Arno Penzias and Robert Wilson would discover the "cosmic background radiation", the "afterglow" of the big bang fireball in which the universe was born 13.82 billion years ago. See my book, Afterglow of Creation (Faber & Faber, 2010).

cost US$1,300, a very large sum at the time. Assembled from wooden rafters, galvanised sheet metal and spare parts from a Ford Model T truck, the dish was nine metres in diameter and weighed two tonnes.*

On completing the mammoth reflector, Reber immediately set about mapping the radio sky. He had a full-time job as an engineer at a radio equipment company in Chicago and his routine was to return to his parents' home, eat dinner and sleep until midnight. From midnight until 6 a.m., when local radio interference was at a minimum, he sat in a little wooden hut watching his telescope track back and forth across the sky. A receiver he had suspended at the focus of the dish picked up the radio static and its magnitude was recorded by pen trace moving up and down on a slowly rotating cylinder of paper.

The smallest detail in the sky that can be discerned by a telescope is determined by both its diameter and the wavelength of the light it collects. Radio waves and visible light are both types of "electromagnetic wave", but radio waves typically have a wavelength about a million times greater than visible light. It means the images obtained by a radio telescope are a million times blurrier than those of a similar sized optical telescope. Reber made his first map of the radio sky at a wavelength of about two metres and the smallest details in it were about fifteen degrees across, or thirty times the apparent diameter of the Moon. Later, he built a receiver that could pick up shorter wavelengths, which made possible a sharper image of the radio

* Grote Reber reconstructed his 31-foot dish radio telescope at the National Radio Astronomy Observatory at Green Bank, West Virginia, where it can be seen by visitors. https://public.nrao.edu/gallery/grote-rebers-telescope-and-the-green-bank-science-center/

sky. Reber, just like Jansky, found diffuse emission from the plane of the galaxy that brightened towards the centre. But his map of the radio sky also revealed something else: an intriguing local peak of emission in the constellation of Cygnus.

One reason nobody, apart from Reber, followed up on Jansky's work was that it was inconceivable to astronomers that there were objects out in space creating significant radio static. Hot bodies like stars emit a thermal, or "black body", spectrum of light and the intensity of that light tails off to pretty much zero at long wavelengths. Reber, however, discovered that for the Milky Way the ratio of the intensity of radio to optical emission was vastly greater than for the Sun. It was the first indication that cosmic radio waves were not being generated by the same mechanism that generated the light of the Sun and stars but by some as yet unimagined exotic process.

Reber published his findings on "cosmic static" in the *Astrophysical Journal* in 1940.[12] But, as was the case with Jansky's work, nobody took much notice. "The astronomers of the time didn't know anything about radio or electronics," he said, "and the radio engineers didn't know anything about astronomy." And of course the Second World War interrupted everything, ensuring he remained for a decade the only radio astronomer in the world.

The war, however, had a profound effect on the fledgling science. A key technology developed by the Allies was the bouncing of radio waves off distant objects such as planes and the detection of their faint echoes. In 1940, "radar" proved a major factor in the defeat of the German Luftwaffe in the Battle of Britain. And, when the war finally ended, so too did Reber's stint as the loneliest researcher in the world. Three groups of ex-radar scientists picked up where Reber had left off. Two were in England – at Cambridge, led by Martin Ryle, and Jodrell

Bank near Manchester, led by Bernard Lovell – and one was in Sydney, Australia.

The man who would take the next key step towards understanding the mysterious radio static coming from the universe was John Bolton. Born in Sheffield, England, he studied physics at the University of Cambridge, where he lodged in a room at Trinity College that was across the Great Court from the rooms once occupied by Isaac Newton. On graduating in 1942, Bolton met with the Royal Navy's recruitment man at Cambridge, the novelist C. P. Snow, who arranged for him to apply for a commission. Bolton subsequently spent two years working on airborne radar, before becoming the radio officer on a British aircraft carrier. His job of maintaining radio equipment took him to the Pacific and to Australia. At the end of the war, a combination of factors – including being turned down for a Cambridge research post, finding the climate in Australia better for the asthma that had dogged his childhood, and having an Aussie girlfriend – led him to stay Down Under. And, in 1946, he had the good fortune to land a job at Sydney's Radiophysics Laboratory. The Laboratory had been set up in 1940 to carry out secret wartime research on radar. But, once the fighting was over, it needed a raison d'être. Among the peacetime applications of the technology considered by the Lab was radio astronomy.

At the time, the principal extraterrestrial interest was in radio emission from the Sun. Late in February 1942, radar stations across England had reported severe bursts of radio noise which stopped them operating for days. The War Office, suspecting the Germans were developing radar-jamming methods, gave the job of urgently investigating the matter to Stanley Hey of the Army Operational Research Group. After analysing the records, he concluded that the radio interference was coming from the Sun. And, when he consulted the Royal Greenwich Observatory, he discovered that it coincided exactly with the passage across the solar disk of an exceptionally active sunspot.

To makes sense of what had gone on in February 1942, the Radiophysics Laboratory decided to create a map of solar radio emission. The problem was that the Sun was a relatively small object in the sky and too tiny for a radio telescope to see in any detail. An obvious way to improve a telescope's "resolution" was to build a bigger one. But this route was blocked because, beyond a certain size, a radio telescope would buckle and collapse under its own weight. One way to overcome this limitation would be to harness together two telescopes. The resolution would then be determined not by the size of each telescope but by their separation. An ingenious way to achieve this had been concocted by Joe Pawsey, the head of the radio astronomy group at the Radiophysics Laboratory and the man responsible for coining the term "radio astronomy".*

The idea was to site a radio telescope on a clifftop. Radio waves are reflected by any electrical conductor and that includes seawater. So, when the telescope points at a source in the sky, radio waves arrive via two distinct routes: directly, and indirectly, reflected off the surface of the sea. In effect, this would conjure into existence a second, virtual, telescope – a mirror-image of the first – separated from it by twice the height of the cliff. The "sea interferometer" was the ultimate buy-one-get-one free.

At the instrument's receiver, the direct and reflected waves

* Pawsey, on a tour of the US, first used the term "radio astronomy" in a letter to Edward "Taffy" Bowen, director of the Radiophysics Laboratory in Sydney on 14 January 1948. The term was quickly adopted. In August 1948, Martin Ryle in Cambridge published a popular article in British Science News entitled "Radio Astronomy".

would undergo "interference". If the peaks of the two sets of waves were in step, they would reinforce each other and create a strong signal; if the peaks of one set of waves coincided with the troughs of the other, they would cancel each other out. Consequently, as the Earth rotated and a source moved across the sky, the signal would reinforce and cancel, reinforce and cancel, creating what are called "interference fringes".* The key thing was that such fringes could be seen only if the source was smaller than the separation of the fringes projected onto the sky. Seeing fringes therefore revealed crucial information about the size of a source.

In 1946, Pawsey built a sea interferometer at Dover Heights. The site was a former Royal Australian Air Force radar station about five kilometres south of the entrance to Sydney Harbour and only a few kilometres from where Captain James Cook had landed at Botany Bay on 29 April 1770. The interferometer consisted of a simple "yagi" antenna similar to an old-style TV aerial. It looked out across the Tasman Sea from the top of 85-metre-high cliffs. Bolton, on starting work at the Radiophysics Laboratory, was assigned to work on the instrument along with a young Australian. Each morning, Bolton and Bruce Slee would get the bus from Bellevue Hill and Bondi Beach, respectively. They would then work at Dover Heights for long shifts in freezing conditions with frequent and frustrating

* An interesting application of this effect may be observed when a helicopter flies above the sea near a radio transmitter. The helicopter receives two signals: one signal directly from the transmitter and a second signal after reflection from the sea. As the helicopter rises the phase difference between the two signals will alter and the helicopter will pass through regions of maxima and minima. See "Lloyd's Mirror" https://www.schoolphysics.co.uk/age16-19/Wave%20properties/Interference/text/Lloyds_mirror/index.html

electricity blackouts. Their workplace misery was compounded by severe postwar shortages that had them smoking tobacco in rolled-up bus tickets.

Neither Bolton nor Slee had any formal training in astronomy, though one of Bolton's lecturers at Cambridge had been Arthur Eddington. Recognising their ignorance, during their night-time observing runs, the two men read textbooks and back issues of astronomy journals borrowed from the physics department library at the University of Sydney. Teaching himself was second nature for Bolton. He had been taken him out of primary school by his parents when he refused to accept the authority of a teacher and the need for classroom discipline. Although his parents were both teachers, he had learnt the most from reading books during his lonely childhood spent roaming the Yorkshire countryside.

Bolton and Slee were tasked by Pawsey to carry out solar observations with the sea interferometer. Unfortunately for them, the Sun had entered a quiescent phase with no sunspots on its surface, so life proved pretty dull. Bolton, however, was galvanised by a report from Jodrell Bank in England. In 1946, Hey had built a pioneering interferometer consisting not simply of one telescope and its reflection in the sea but of two actual telescopes. Using it, he had found a localised source of radio waves in the constellation of Cygnus, exactly where Reber had earlier discovered a peak of emission. The possibility that there might exist localised radio sources – radio stars – blew Bolton's mind. In June 1947, he and Slee confirmed that there was indeed a compact, point-like source of radio waves in Cygnus.

Unfortunately, Bolton and Slee were not discreet about their off-piste observations. When Pawsey, on a visit to Dover Heights, noticed they were not observing the Sun, he sent them back to Sydney in disgrace. Bolton was reassigned to work with

New Zealander Gordon Stanley on building instrumentation for an expedition to Brazil to observe radio emission during a total eclipse of the Sun. But his luck was in. After a few months, it became obvious that the expense and logistical problems of taking people and equipment halfway around the world were too much, and the expedition was cancelled. Pawsey told Bolton he could cannibalise the eclipse equipment for his own projects – and he could use Stanley.

With a truck filled with equipment, Bolton, Slee and Stanley headed back to Dover Heights. Their priority was to rig up a radio so they could listen to a broadcast of the fifth Test Match between England and Australia at the Sydney Cricket Ground. After that, they installed two new receivers. This time, when they pointed their antenna at the Sun, the pen recorder went crazy. One of the largest sunspots for several years was transiting the solar disk. The radio outburst came from an accompanying solar flare, which ejected large amounts of matter into space at high speed. The event was so powerful that the following night a bright aurora was visible over Sydney, an extremely rare event at a latitude as high as thirty-four degrees South.[13]

When Bolton, Slee and Stanley finished with the Sun, they started scanning the heavens. To their delight, they found several more compact radio sources in addition to the one in Cygnus: in the constellations of Taurus, Centaurus and Virgo. But their radio-vision was too blurry to reveal their exact locations. What was needed was a telescope with finer resolution, which in practice meant an even bigger separation between the yagi aerial and its sea image. Finding that there were no suitable sites close by in Australia, Bolton and Stanley looked further afield and found a site on the North Island of New Zealand. The cliffs at Pakiri Hill, about 70 kilometres north of Auckland, were 280 metres high, making them more than three times taller than those at Dover Heights. In 1948, Stanley converted an army radar trailer into a mobile sea interferometer and sent it to Auckland by sea. Stanley and Bolton followed later on a flying boat.

It took three months of painstaking observations followed by several months of gruelling data reduction on pen and paper. But, crucially, they measured the location of their compact radio sources to within half a degree – the apparent diameter of the Moon – raising the hope of linking them to unusual astronomical objects on photographic survey plates.

Bolton adopted the practice of labelling the radio sources in a particular constellation that were brightest, second brightest, third brightest, and so on, with the letters of the alphabet. In 1949, Taurus A, one of the sources, was identified with the Crab Nebula, the glowing remnant of a massive star that had detonated as a "supernova" and shone so brightly in the night sky of AD 1054 that the Chinese had recorded it as a "guest star". The identification of Taurus A with the Crab was critically important because for the first time it created a bridge between the new science of radio astronomy and conventional astronomy, kicking off a postwar revolution. No longer would astronomers be limited by what they could see through optical telescopes. Radio waves, which easily penetrated clouds of choking interstellar dust, opened up a new window on the universe. In due course, astronomy, restricted for so long to observing celestial bodies with eyes sensitive only to the single octave of wavelengths of visible light, would be supplemented by fifty-six octaves of the electromagnetic spectrum, ranging from ultralong radio waves to ultrashort gamma rays.[14]

But what would turn out to be the most significant discovery of the sea interferometer was not the radio source associated with the Crab Nebula but the mysterious radio sources in Centaurus and Virgo, and of course Cygnus. Bolton strongly suspected that Centaurus A, Virgo A and Cygnus A were extragalactic. However, he was acutely aware that he had no explanation for the enormous power output necessary for them to be detectable over such huge distances. He also knew that the astronomical community was very conservative. Consequently, in a paper on the discrete sources published in *Nature* in 1949, he, Stanley and Slee went along the orthodoxy that the compact radio sources were nearby radio stars in our galaxy.[15],[16] In fact, claiming anything different would have meant also explaining how the sources could fluctuate in brightness on short timescales, indicating they were much smaller than a galaxy.

It was later found that the brightness fluctuations were caused mainly by an interplanetary version of "twinkling" in which irregularities in the Earth's atmosphere cause the light coming from stars to jitter. Rather than being in the air, the irregularities making the radio waves twinkle are in the charged gas, or "plasma", streaming outward through the solar system from the Sun. Twinkling is obvious for celestial bodies that appear tiny like stars but not for ones that appear big like the Moon. So regardless of whether the fluctuation in the radio sources was intrinsic to the sources or whether it was the result or interplanetary twinkling – "scintillation", to give it its technical name – it came to pretty much the same thing. The sources were small – much smaller than a galaxy.

By 1950, however, the idea that compact radio sources in Centaurus, Virgo and Cygnus were exotic stars in the Milky Way had bitten the dust. All were identified with peculiar "elliptical" galaxies at enormous distances: Centaurus A was associated with NGC 5128, which was bisected by a prominent dust lane; Virgo A was twinned with NGC 4486, which had a strange optical "jet"; and Cygnus A with a galaxy called NRAO 620. Without doubt, finding extragalactic radio sources was one of the most shocking discoveries in the history of astronomy. To be detectable at large distances beyond the Milky Way, such sources must be extremely powerful – pumping out up to 100 times the energy radiated by all the stars in our galaxy – and all this energy had to be coming from a region far smaller than a galaxy.

In fact, evidence that something strange was happening deep in the cores of some galaxies had been found at the start of the twentieth century by a German astronomer. In 1908, Edward Fath at Lick Observatory near San Jose, California had found strange "emission lines" in the spectrum of the spiral galaxy NGC1068. Such lines are usually seen only in gaseous "nebulae" floating between the stars. They arise when electrons in atoms of the gas are kicked into a high-energy state before dropping down and emitting light. The kicking needs to be done by a high-energy, high-intensity source of light. In the case of nebulae – the birthplace of stars – it is ferociously hot newborn stars. In the case of NGC 1068, the powerful energy source was a total mystery.

More evidence that the hearts of galaxies were the seats of enormous energies came during the Second World War. In 1943, Carl Seyfert, using the Mount Wilson 2.5-metre telescope, discovered six galaxies with anomalously bright "nuclei". These "Seyfert galaxies", as they became known, all had the strong emission lines seen by Fath. Each line spanned a large range of wavelengths. Assuming this "broadening" was caused by the Doppler effect, Seyfert deduced that the emitting gas must be moving incredibly fast, at up to 8,500 kilometres a second. What was the energy source and why was the gas moving so tremendously fast? Nobody bothered to address the question because Seyfert's galaxies did not fit the accepted picture of such objects. Seyfert, discouraged, abandoned his research.

But not everyone ignored the maverick galaxies. One Soviet astronomer was convinced that something highly unusual was going on in galactic nuclei. At the 1958 Solvay Conference, held in Brussels, Viktor Ambartsumian argued for a radical change in our picture of the nuclei of galaxies and for the rejection of the idea that they are made of stars alone. "Large masses of pre-stellar matter are present in nuclei," he declared, cryptically.[17]

Ultimately, the sea interferometer was limited in the fine detail it could see by the height of the available cliffs. But this blurry eyesight, Hazard at Jodrell Bank had shown, could be overcome by building interferometers with two physical telescopes, moveable on railway tracks to a range of separations. In the late 1950s and early 1960s, other radio astronomers followed Hazard's lead, using two or more dishes to mimic, or "synthesise", larger radio telescopes.

In all these developments, the US was left behind by Australia and Britain. But, in 1955, Caltech poached Bolton. He founded a radio observatory in the Owens Valley, a five-hour drive north of Los Angeles between the Sierra Nevada Mountains and the White Mountains. Among the sage brush and jack rabbits, 1200 metres up in the High Desert, he supervised the construction of two 90-foot dishes on 1,600-feet-long north-south and east-west railway tracks. The "90-foot interferometer" put Caltech at the forefront of work to pin down the location of the mysterious cosmic radio sources. On its completion in 1960, a Canadian postdoctoral student called Tom Matthews started going through the 3C catalogue methodically, pinning down the location of each radio source, some to within ten arcseconds, or less than 1 per cent of the apparent diameter of the Moon.

Meanwhile, Allan Sandage looked for optical counterparts on photographic plates of the Palomar Observatory Sky Survey.

The very first radio source from the Cambridge catalogue for which Matthews and Sandage scored a success was 3C 48. In October 1960, Sandage found the sixteenth magnitude star whose mysterious spectral lines so baffled Greenstein. Another radio source, which showed every indication of being very small, was 3C 273. Unfortunately, Matthews' location was not good enough to find a unique optical counterpart. However, in 1962, the Moon was to pass in front of 3C 273 several times. Since the Moon's orbit, and so its position in the sky, was extremely well known at all times, there was the possibility of exploiting this "occultation" to reveal the precise whereabouts of 3C 273. All that was needed was to record the precise time at which the radio source vanished behind the Moon and when it reappeared. However, the occultation would visible only from the southern hemisphere.

Bolton was in the right place at the right time. In 1960, much to the dismay of Caltech, he had returned to Australia to supervise the construction of a giant 64-metre radio dish. Designed by Barnes Wallis, of Second World War bouncing bomb fame, it was situated at Parkes in New South Wales. Bolton, therefore, had the rare distinction of founding two major observatories: one in the northern and one in the southern hemisphere. None of this was a surprise to those who knew him. His central characteristic was his phenomenal determination. Whether playing cricket, table tennis, snooker or golf, he would invariably prevail even when facing a better opponent. He brought the same unshakeable resolve to the task of hunting down the extragalactic radio sources.

The giant Parkes dish had become operational in 1962 and was ideal for observing the lunar occultation of 3C 273. At

Jodrell Bank, Hazard had demonstrated that such occultations could pin down the location of radio sources to unprecedented accuracy. As luck would have it, he happened to be in Australia, so Bolton invited him to be a "guest observer".

The lunar occultations of 3C 273 would occur on 15 May, 5 August and 26 October 1962. Of the three events, the most important was 5 August because both the disappearance and reappearance of 3C 273 would be visible from Parkes. Unfortunately, the 5 August occultation was so low in the sky that it would be hard for the 64-metre dish to observe it. Bolton's solution was to disable the failsafe device that cut off the power to the dish if it pointed too close to the horizon. For good measure, he also removed a ladder from the telescope structure and, with the aid of a grinder, cut away "housings of the zenith angle bearings", the steel balls that reduced friction as the dish changed from pointing near the horizon to the zenith.[18] He had acquired this kind of improvisational skill on Royal Navy ships during the war when he was under constant pressure to fix temperamental radio equipment to deadlines and in difficult combat conditions.

Though Hazard carried out extensive preparations over many weeks, the run-up to each occultation proved a nail-biting time. All roads to the observatory were closed and all unnecessary electrical equipment on site turned off. During the occultation of 5 August, the rim of the Parkes dish very nearly scraped the ground. But everything worked. And, crucially, the three occultations pinned down the precise location of 3C 273.

Hazard sent the location to Schmidt at Caltech, who immediately consulted the photographic plates of the Palomar Observatory Sky Survey. At the location of 3C 273, he found a magnitude 12.9 star with a curious jet extending from it. It was the same object whose spectrum he had taken at the prime focus of the 5-metre telescope on 29 December 1962. It was the same object whose mysterious spectral lines made no sense whatsoever until his dramatic discovery on the afternoon of 5 February 1963.

PASADENA, 1.15 A.M., 6 FEBRUARY 1963

For several hours after Corrie and the girls had gone to bed, Schmidt paced up and down his living room like a caged tiger.[19] He could not stop. He could not sit down. Too many thoughts were flying through his mind. In his Caltech office, he, Greenstein and Oke had struggled all afternoon to come up with an explanation of the crazy spectra of 3C 273 and 3C 48 that would allow them to be no more than maverick stars in our own galaxy. Might the mystery lines be caused, for instance, by bizarre ionised states of rare elements? But, no, that, did not work. And neither did anything else they tried. By 6 p.m., they were exhausted and drove over to Greenstein's house in Duarte. They had never done that before.

Greenstein's wife, Naomi, was flabbergasted when her husband burst through the front door yelling: "We need a drink!" Evidently, he had never done that before either. On the terrace above the garden with the faint whiff of skunk in the air, they had sipped ice-cold beers. The pollution hanging over the Los Angeles basin was creating a spectacular red sunset. Naomi brought out guacamole and tortilla chips and Schmidt thanked her, politely, but the other two were too caught up in their heated discussion to even notice. A priority, said Greenstein, was to get the discovery into print. Urgently.

It was of course Bolton's letter to Schmidt, asking him to submit a paper to *Nature* to go alongside Hazard's on the occultation of 3C 273, that had spurred him to take another look at the object's spectrum, compare its lines with the Balmer series and make his discovery of its ludicrously high red shift. At the time, his worry was that he had too little to say about the spectrum of 3C 273 to fill a paper. Now the problem was what to leave out. In fact, there was so much to say that the three of them decided to each submit a paper to *Nature* on 3C 273 and 3C 48. Now that they knew they were definitely not stars, they were calling them "quasi-stellar radio sources".[20] It was clumsy and long-winded but none of them could think of anything better.

For several hours, with the distant yip-howls of coyotes coming from the foothills of the San Gabriel Mountains, they had argued over what the spectra of 3C 273 and 3C 48 actually meant. But when Schmidt left for home at around 8.30 p.m., none of them were any the wiser. A brilliant Moon, still two days from full, was in the sky as he drove back along the Foothill Freeway to Pasadena. It was the same Moon whose mountains and craters he had seen through his uncle's telescope from the upstairs floor of his pharmacy in Bussum, so bright they had to put a dark filter in front of the eyepiece to avoid being dazzled. It was the same Moon whose mountains and craters made the lunar rim jagged and set an ultimate limit on the accuracy with which a lunar occultation could locate 3C 273.

When he got home, the first thing he said was: "Corrie, something terrible happened at the office today!" The look of worry that flashed across her face caused him to immediately backtrack. He had not quite meant that. But, in a sense, what he had discovered was terrible. Terrible because he was a fundamentally shy man who enjoyed working without fuss in a quiet corner of science, and he knew he would now have to go public with a discovery that would make headlines across the world and thrust him into the limelight. That was one of the reasons he was pacing up and down his living room at 1.15 in the morning. But it wasn't the only one.

What if they were wrong? What if they had missed something? What if it was a big trap and, after they published, someone would come up with a simple explanation of 3C 273 and 3C 48 that showed things were not so extraordinary after all? Other scientists would laugh at them. How could they have been so stupid as to make such a mistake? How could they have been so gullible to think a star of thirteenth magnitude could be at a distance of 2 billion light years?

Earlier, pulling out of the Caltech parking lot onto California Boulevard to drive to Greenstein's, he had spotted the physicist Richard Feynman coming towards him. "Dick!" he exclaimed out of the wound-down window. "You won't believe this!" He was right. Feynman did not believe him. It was preposterous that 3C 273's huge red shift could be cosmological. "What about a gravitational red shift?" Feynman, dammit, was right. Before making their claim, they must first rule out the possibility that the red shift of 3C 273 was caused by the light climbing out of the gravitational well of some strange super-dense object.

But, if they were right and 3C 273 and 3C 48 were really at the enormous distances indicated by their red shifts, that in itself was a huge problem. What the hell could be liberating such a phenomenal amount energy from so small a volume?

How could he admit to journalists that he had no absolutely idea? They were not simply claiming a discovery on the basis very little evidence; they were claiming a discovery for which they had no plausible explanation.

As Schmidt continued to pace, yet more thoughts crowded his mind. If objects this far away were so bright and easy to see, it must mean that fainter objects in the same class existed that were even further away. And, because their light would take so long to reach us, they would be beacons blazing in the dawn of time. Using them, it would be possible to probe not only the deepest reaches of space but also the earliest moments of the universe. With that thought, he finally stopped pacing. Through the living room window, the white dome of the Hooker Telescope was glinting in the moonlight on the dark summit of Mount Wilson. It was from that observatory high above Pasadena that, in 1923, Edwin Hubble discovered the sheer, mind-cringing vastness of the universe: that our Milky Way was merely one giant island of stars among billions upon billions of other galaxies. But Hubble had no idea. 3C 273 and 3C 48 were far, far beyond any galaxy he had observed. They were bonfires burning in the most distant reaches of the cosmos and they promised to illuminate a universe far vaster than any of them had ever imagined.

The existence of 3C 273 and 3C 48 had put a bomb under the world of astronomy. There was no doubt about it. Schmidt could feel a new world, a new universe, opening up before him. He had a sudden thought that made him feel giddy. In a hundred years' time, when the history of astronomy was written, the subject would be divided into two parts: "Before 5 February 1963" and "After 5 February 1963".

*

The year after Maarten Schmidt's discovery, a Chinese-born American astronomer wrote an article in the May 1964 of the magazine *Physics Today*. In it, Hong-Yee Chiu coined the term "quasar".[21] It stuck.

By rights, quasars should have been discovered almost three years earlier. On 16 November 1960, just a month before leaving Caltech for Parkes in Australia, Bolton wrote a letter about 3C 48 to Pawsey at Sydney's Radiophysics Laboratory[22]: "I thought we had a star. It is not a star. Measurements on a high dispersion spectrum suggest the lines are those of neon [V], argon [III] and argon [IV], and that the redshift is 0.367. The absolute photographic magnitude is -24 which is two orders of magnitude greater [100 times more luminous] than anything known…"

Bolton did not have the courage of his convictions perhaps because he was first and foremost a radio engineer and felt himself an interloper in the world of astronomy. Instead, he allowed himself to be swayed by those with more experience. And no one at Caltech had more experience than Greenstein, who convinced Bolton 3C 48 was a star.

In December 1963, only nine months after Schmidt's discovery, the world's astronomers met in Dallas for the First Texas Symposium on Relativistic Astrophysics. Schmidt was asked to give a talk on quasars. He suspected, however, that there would be a media frenzy – exactly the thing he had so feared when pacing up and down his living room that restless night of 6 February. Knowing how deeply uncomfortable he would feel caught in the glare of the media spotlight, he turned down the offer. "I agonised about publicity," says Schmidt. "The publicity was an enormous pressure on me."

The organisers of the symposium, who had hijacked the discovery of quasars to put their conference on the scientific map, were dumbfounded by Schmidt's polite refusal of their offer. But no amount of persuasion proved enough to winkle the publicity shy Dutchman out of his protective shell. Although Schmidt attended the conference, he refused to talk about the discovery of quasars and instead insisted that Greenstein, his senior colleague, present the findings.

The Dallas conference was where Roy Kerr presented his exact description of the shape of a space-time around a spinning black hole. It was a huge moment in the history of science: the first significant development in Einstein's theory of gravity for forty-seven long years. But nobody – not even Kerr himself – realised he had provided the answer to the quasar puzzle.

The solution was proposed independently by the American astrophysicist Ed Salpeter and the Soviet astrophysicists Yakov Zeldovich and Igor Novikov in 1964. Quasars are powered by spinning, or "Kerr", black holes. The previous year, Matthews and Sandage had pointed out that it would require the gravity of about a billion times the mass of the Sun to hold onto the gas in 3C 273 and 3C 48, which according to the Doppler width of the spectral lines was expanding at 1,000 kilometres per second.[23] Salpeter and Zeldovich picked up on this idea and proposed that quasars are powered by spinning "supermassive" black holes with masses ranging from tens of millions to tens of billions of times the mass of the Sun. Matter – and ripped-apart stars – swirls down onto such a black hole like water down a plug hole, heated by internal friction to millions of degrees. This blisteringly hot "accretion disk" of in-swirling matter generates the prodigious light output of a quasar. Whereas nuclear fusion – the power source of the Sun and stars – turns about 1 per cent of the mass-energy of matter into other forms such as light and heat, matter funnelling down through an accretion disk onto a black hole can convert more than 40 per cent, if the black hole is spinning at its maximum rate possible.

The spinning supermassive black hole model of Salpeter and Zeldovich received little attention, perhaps because multi-billion-solar mass black holes sounded like the stuff of science-fiction. However, by the time the idea was fleshed out by Cambridge astrophysicist Donald Lynden-Bell in 1969, more astrophysicists had come around to the idea.[24] "A quasar's thirst is gigantic," says Heino Falke of Radboud University in Nijmegen in the Netherlands. "It devours forty-five times the total amount of water on the Earth every second – the equivalent of the mass of the Sun every year… With every sip it only gets heavier, bigger. More attractive, more dangerous."[25]

What is remarkable is that the first theorists to imagine black holes such as Chandrasekhar to Oppenheimer failed to anticipate their most striking characteristic. They believed that such bodies, on account of being black against the black of space and very tiny, would be impossible to see. They failed to realise was that, out in the universe, black holes are likely to be embedded in an environment of interstellar gas and ripped-apart stars. In gobbling it up, they would super-heat it. Far from being black, black holes could be the most brilliant beacons in Creation.

What type of beacon they were depended on a number of factors. "With different values of the [black hole mass and accretion rate]," wrote Lynden-Bell, a former postdoctoral student at Caltech, "these disks are capable of providing an explanation for a large fraction of the incredible phenomena of high energy astrophysics, including galactic nuclei, Seyfert galaxies, quasars and cosmic rays."

It was a prescient remark. Quasars turn out to be the brightest members of a large class of galaxies with violent activity in their nuclei. Such "active galactic nuclei", or AGNs, are defined by the fact that the majority of their light comes not from stars, as it does in a normal galaxy, but from light given out by superheated matter swirling down onto a central black hole. Different members of the class appear different because of variations in the mass of their central black holes, variations in environment in which the black hole is embedded, and variations in the angle at which we happen to be viewing the accretion disk.

Another type of active galaxy, in addition to the quasar and Seyfert galaxy, is the "radio galaxy". When observing them, the first interferometers whose individual dishes had a large separation such as Caltech's 90-foot interferometer at Owens Valley found something striking and baffling. The radio emission comes not from the visible galaxy but from enormous "lobes", which dwarf the central galaxy, one on either side.

It was obvious from this "double-lobe" structure that there must be a connection between a central galaxy and its radio lobes – some kind of channel by which matter was funnelled outwards from the nucleus. But it was clear it would require a significant leap in the size and collecting area of interferometers to see it. In the early 1980s, an interferometer array of twenty-seven linked radio dishes was constructed in the New Mexican desert near Socorro. The Very Large Array imaged for the very first time thread-thin "jets" of matter stabbing out from central galaxies to feed radio lobes. Some objects, such as 3C 273 and the bright "nucleus" of M87, even sport optical jets extending from their nuclei. The jets reveal that, although the defining characteristic of a black hole is that that they suck in matter, the most striking observational characteristic of many of the black holes observed by astronomers is that they are blowing out matter. Another commonly held idea, in addition to black holes being black, turned on its head.

Although a jet may lance outwards across space for millions of light years, astronomers can zoom in on its point of origin using a technique which harnesses radio dishes around the globe to simulate an Earth-sized radio telescope. Very Long Baseline Interferometry, or VLBI, often reveals a remarkable structure in the innermost few light years which astronomers have dubbed a "cosmic blow torch". The imaging technique may also show something scarcely believable if the jet happens to be pointing in our direction, but at a small angle to the line of sight. Knots of plasma appear to surge along it at speeds of up to ten times the speed of light. This is, of course, impossible and must be an illusion. In fact, "superluminal motion" was anticipated by Cambridge astrophysicist Martin Rees in 1966.[26] It is caused by the material that is emitted at one time moving so fast that it almost catches up the light given out by material at an earlier time. Astronomers underestimate the interval between the two emissions, so, when they divide the distance travelled by the knot by the time to yield the speed, they overestimate the true velocity.

But, although superluminal motion may not be evidence of faster-than-light motion, it is nevertheless evidence that matter is being accelerated to within a whisker of the speed of light. It serves to underline the prodigious power of active galactic nuclei. Whereas on Earth we can boost an infinitesimally small amount of matter to near the speed of light with a giant particle accelerator like the Large Hadron Collider near Geneva, every year a typical quasar is able to accelerate a mass equivalent to the Sun or more to within a whisker of the ultimate cosmic speed. The details of how they do this is not understood but the ultimate source of the energy is clear.

Although the Penrose mechanism for extracting energy from the ergosphere of a black hole is too inefficient, a related mechanism, proposed in 1977 by Roger Blandford and Roman Zjanek of the University of Cambridge, is much more promising.[27] The Blandford–Znajek process recognises the importance of magnetic fields.[28] These are naturally generated by the charged "plasma" of the super-hot accretion disk. And, when material falls into the supermassive black hole, the magnetic field lines end up threaded through the event horizon like the spines of a porcupine. A spinning magnetic field generates an electric field, which can drive an electric current. This "dynamo" mechanism is the basis of how we create electricity on Earth. In the case of active galactic nuclei, the spinning magnet of supermassive black hole creates an enormous electric field between its poles that is more than enough to accelerate electrically charged matter such as electrons at relativistic speeds along the jets. The exact manner in which the jets are launched is not known and neither is it understood how they remain collimated, thread-thin channels over millions of light years.

The existence of powerful magnetic field and high-energy electrons turn out to be the two prerequisites for the mechanism that ultimately explains the intense radio emission from celestial objects such as quasars. It had been guessed by Bolton and Stanley when they detected radio waves from a solar flare. The activity on the Sun was associated with both strong magnetic fields and electrically charged matter, or "plasma", moving in response to those fields. Somehow these two ingredients combined to create intense radio emission. Might the mechanism that generated radio waves on the Sun, Bolton asked, be similar to the one generating the radio waves from extragalactic sources? His speculation would prove to be prescient.[29]

Bolton and Stanley had no idea how the two ingredients combined to generate the radio emission of the extragalactic radio sources. However, in the early 1950s, physicists accelerated electrons to high energy by confining them by a magnetic field and whirling them around a subatomic racetrack. The Achilles' heel of such a "synchrotron" is that, as the electrons gain energy, they also lose it by radiating electromagnetic waves known as "synchrotron radiation". But what was the bane of the life of particle physicists was a boon to astrophysicists. It became clear to them that if, out in space, there were high-energy electrons and strong magnetic fields, the magnetic force on the electrons – which is always perpendicular to the field – would cause the electrons to spiral around the field direction and emit intense synchrotron radiation in the form of radio waves.

Astronomers had been mistaken in believing that the sun and stars generate negligible amounts of radio waves. The sun has both high-energy charged particles and magnetic fields and so emits synchrotron radiation in the form of radio waves. And, sure enough, the radio waves from active galaxies – specifically, how their intensity changes with wavelength – bear the characteristic fingerprint of synchrotron radiation.

The synchrotron mechanism of radio emission explains why optical maps of the sky do not match radio maps of the sky. Whereas visible light is emitted principally by solid things like stars, radio waves are generated by immense volumes of relatively empty space in which high-energy electrons spiral around magnetic fields.

Together, the jets and the accretions disks help explain the variety of active galaxies. The disks are so hot that they puff up into a sort of doughnut ring around the central black hole. If the jets emerge perpendicular to our line of sight, we see them as thread-thin channels, stabbing outwards from the central galaxy. When they slam into the intergalactic medium, plasma splashes back, like water from a hose hitting a brick wall, creating the double lobes of radio galaxies, the biggest "objects" in the universe. If, on the other hand, we happen to be looking straight down through the doughnut ring towards the black hole, we see the jet coming straight towards us. In this case, the light is hugely boosted in intensity by a process known as "relativistic beaming" and we see a different type of active galaxy known as a "blazar".[30]

Quasars were suspected to be star-like because their accretion disks were so luminous that they completely overwhelm the light of the stars in their parent galaxies. In fact, the possibility that the galaxies of 3C 273 and 3C 48 were hidden by the glare of their nuclei was suggested by Matthews and Sandage as early as 1963. And, indeed, in 1983, when sensitive enough instruments were built that could detect ultrafaint light, this was found to be the case.[31]

Some Seyfert galaxies show spectral features nearly identical to those seen in quasars and they turn out to be closer and less powerful versions. Tragically, Seyfert never knew the importance of his discovery. He died in a car crash in Nashville on 13 June 1960, less than three years before the discovery of quasars.

In 1965, Sandage reported the discovery of a large population of radio-quiet objects that otherwise appeared to resemble quasars.[32] Only about 10 per cent of quasars turn out to be radio-loud. This is because only 10 per cent of quasars have the jets necessary for generating radio emission. But why this is so remains a mystery.

Maarten Schmidt died at his home in Fresno, California, in 2022. He was ninety-two. Though he had been desperate to avoid the media spotlight, there was nowhere to hide after *Time* magazine put him on their cover in 1966.

John Bolton died in Australia in 1993 at the age of seventy-one, never having lost his Yorkshire accent. After his death, his ashes were buried in the ground beneath the sundial at Parkes.* A sometimes difficult man who could be harshly intolerant of mediocrity and poor judgment in others, he nevertheless was a devoted father to his wife Letty's sons by her first husband, killed in the war, and he kept an open house for his staff, barbecuing steaks and providing fine wines. The British astronomer and physicist Robert Hanbury Brown said: "How can you plan serendipity? I think that you need the right man in the right place at the right time, but he must be a man who doesn't know too much!" Bolton was just that. His relentless pursuit of the extragalactic radio sources opened up the universe and gave birth to modern astronomy.

Active galaxies, of which quasars are the most violent examples, constitute only about 1 per cent of all galaxies. Therefore, it was still possible to sweep supermassive black holes under the carpet, to believe that they are rare anomalies in nature and are only of peripheral importance in the universe. But then, on 24 April 1990, NASA launched the Hubble Space Telescope. And everything changed.

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* Parkes played a key role in the Apollo 11 Moon landing on 20 July 1969 as well at the rescue of the stricken Apollo 13 spacecraft in 1970. Bolton was portrayed by Sam Neill in the 2001 Australian movie The Dish.