Thirty-five years ago, when research students joined the Cambridge Radio Astronomy Group they were presented with a set of tools. It was very nice that the Cavendish could afford to give tools to all of us, but it was also a very clear statement about what kind of work you were expected to do. In fact, I spent the first two years of my PhD “in the field”, in one field in particular on the Barton Road about three miles from the center of Cambridge, at the Lords Bridge Radio Astronomy Observatory.

In an area the equivalent of two football pitches, six of us built an array of a thousand wooden posts, 2048 cooper dipoles and 120 miles of wire and cable. It operated at 81.5 MHz and took about two years to build. We built the telescope at the height of the Rhodesian copper crisis, using several tons of copper wire, and we always had nightmares that we would have a neat way of picking out the quasars.

I was primarily responsible for the cables and plugs. John Pilkington mass-produced antennae and feeder wire and from time to time almost got tangled up in birds nests of cooper wire, and we always had nightmares that we would come out one morning to find someone had been round with wire cutters and removed the copper. It had happened to one of the subsidiary radio telescopes, but it didn’t happen to this one.

I was spared most of the sledgehammering but nonetheless when I left I could swing a sledgehammer. I was spared most of the sledgehammering but nonetheless when I left I could swing a sledge. So my first sledge was in a project to identify as many quasars as possible in the sky visible from Cambridge, and to have a stab at measuring their angular diameters. And in fact, that is what my thesis was about, because by the time pulsars came along, my supervisor, Tony, advised me that it was too late to change the thesis’ title. From what I now know about university systems, I think he was wrong, but as a PhD student I believed him. So the pulsars went in an appendix and I wrote a substantial thesis on the angular diameters of quasars using an interplanetary scintillation technique, all done within a three-year period.

An important factor in this story is that the scintillation, the “twinkling”, is quite rapid, and if you’re going to
“see” twinkling you have to have a system that responds fast enough to follow the changes in brightness. So the instrument has to have a short time constant, like making a rapid exposure with a camera. If you have a short time constant you lose some of the advantages of integrating for a long time. You have problems of signal-to-noise ratio and the way you get round them is to increase the collecting area of your radio telescope. Hence the 4.5 acres of radio telescope operating with a time constant of something like a tenth of a second—a combination that had not been used before. After the two years building the radio telescope the rest of the construction team moved on to other projects and I, the research student, was left to operate the telescope. It was a very simple operation: you scanned one strip of the sky; the next morning you went out to your telescope, flipped a few switches and scanned the next strip of the sky; next morning you went out and set the telescope to scan the next strip; and so on, day after day. Exciting isn’t it? Just like all PhDs!

MILES OF CHART PAPER

There weren’t many computers in those days. In Cambridge, there was Titan and the radio astronomy group had some time on it, but that time was used for the aperture synthesis of the One Mile Telescope results, and those of us on other projects did not have access to any computers. We used research students instead. We output our signal on paper charts, red pen over moving paper, and then we analyzed the paper charts. This telescope produced 100 feet of chart paper every day and one complete scan of the sky took four days or 400 feet of paper.

One of the things you have to get used to when you start operating a radio telescope is the effect of interference and how it appears on the charts. And we very quickly identified interference—it was usually strong enough to wipe everything else out. We also got used to identifying the scintillating quasars. There were a goodly number of those—although we weren’t clear we were measuring the angular diameters that well. But it was clearly a successful project. As the only student on the project it was my job to analyze those hundreds of feet of chart paper. It was quite a job just keeping up with it and my logbook has dismal statements like “now 1000 feet behind with the chart analysis” and “now 2000 feet behind with the chart analysis.” In the six months that I personally operated the telescope, several miles of chart were recorded.

A scientist, particularly somebody trained in the physical sciences, has a brain that stores problems, such as things one doesn’t understand. Those of us who have trained as physicists have learned to be economical with our brains. We know that if we understand something we don’t need to worry, but if there’s something we don’t understand, we file it somewhere. In among each 400 feet of chart paper there was occasionally a quarter inch that I did not understand. What niggled me about that quarter inch was that it didn’t look like a scintillating quasar, and it didn’t look like interference. It was a bit of a puzzle. A further puzzle was that it was intermittent. The first few times I saw this I noted it as a query. But by the second or third time I’d seen this funny, scruffy signal, my brain cells were beginning to connect and said “I’ve seen this sort of signal before. I’ve seen this sort of signal, from this bit of the sky before, haven’t I?” And then it’s easy. You get out the charts from previous runs that cover that bit of sky; you spread them out all over the floor so that you can see them, and you realize that yes, you have occasionally seen a quarter inch of signal like that before from that bit of the sky.

I talked to my supervisor. One of our ideas was that it might be a particularly compact source, useful for calibration. In retrospect this was a silly idea because it didn’t explain the one-sided nature of the spikes that made up the signal. But when you’re struggling you don’t always reconcile all the information. So we planned to make the equivalent of a photographic enlargement. We wanted this signal to take up not just a quarter inch but be spread out so that we could see the structure. What we needed to do was to run the chart paper faster, but we couldn’t afford to run the chart paper at that speed for 24 hours a day—it would run out. And of course, it’s the research student’s job to handle these sorts of things.

So I had to go out to the observatory each day at the appropriate time, switch on to high-speed recording, run it for the duration of the transit, and switch it off again. And for a month I did that. This was an intermittent source which wasn’t always there every time you looked at that patch of sky, and of course, it had “intermitted away” each time I went out to observe it with the high-speed recording. For a month I made high-speed recordings of receiver noise and background noise. One day I thought “Sod this!” There was a very interesting lecture in Cambridge, about age and background noise. I remember it vividly, partly because of where it
fell in my life, but partly because it is a topic that becomes more relevant as you get older. For the first and last time I skipped going out to the observatory that day and went to the lecture; it was a very good talk. I went out to the observatory the next morning and there was the signal!

My supervisor had been getting cross as this month of non-results proceeded. “It’s a flare star and it’s been and gone and done it and you’ve missed it!” he said. So the day after the lecture I stayed out at the observatory—not daring to go back into Cambridge, and on the high-speed recorder picked up a series of pulses, a weak signal that was obviously very close to the detection threshold with some of the pulses missing, but keeping phase and keeping very precise period. You could see even as the chart flowed under the pens the regularity of the blips and you could see the period was about one-and-a-third seconds. As soon as the transit was over and the recorder was switched back to normal speed I took this pen recording and laid it out on the floor and with a ruler established that the period was accurately maintained at least for the length of the recording. It’s very interesting, your reactions when you see this kind of thing. I had been well-trained as an undergraduate at Glasgow University and when I saw this pulse signal coming in, one half of my brain was saying, “Gee whiz it’s a pulsed signal”, and the other half of my brain was saying, “What do I do next?”

**It Must Be Man-Made**

We didn’t make telephone calls with quite the same alacrity then, but I called up my supervisor who was teaching in an undergraduate physics laboratory. He’d probably been dealing with some twit of a Cambridge undergraduate who thought his grating had three lines per inch, and was then phoned up by his twit of a research student who says, “Tony, you know that funny scruffy signal—it’s a string of pulses one-and-a-third seconds apart.” Tony’s response was: “That settles it then—it must be man-made.” Now, Tony was a better astrophysicist than I was at that stage. I did not realize that a period of 1.3 seconds is really rather small for a star. I did appreciate that a pulsed signal was very peculiar and I did appreciate that 1.3 seconds sounded artificial. You can imagine somebody setting a signal generator at that rate.

Tony was interested enough to come out to the observatory the next day at the appropriate time. This was an anxious moment given how low level these signals were and how infrequently we detected them; it might not have been visible that afternoon. But bless it, it performed! Tony saw with his own eyes a string of pulses coming and that they were equally spaced, and that they were equally spaced at the same period as the previous day; so there’d been no change in period over 24 hours—no surprise given what we now know of pulsars. And that’s where our troubles began.

People have asked me, “Was it exciting discovering the first pulsar?” No! It was scary and it was worrying. Finding subsequent ones was great, but finding the first one was not. Tony was quite convinced that there was something wrong, that it was an artificial something or other. And of course the place you start is with your own equipment. I had wired up this radio telescope and was scared that I had literally got some wires crossed, that my stupidity was about to be discovered by the combined brains of Cambridge, and I might be leaving without a PhD. Our first task was to ask a colleague and his research student with a telescope that operated at the same frequency to see if they too could pick up the signal. We used what had been the 4C radio telescope (now kitted out with an 81.5 MHz receiver) and the memory is still vivid. The signal showed first in my radio telescope, so we knew the source was there and performing. Then we moved over to stand by the chart recorders for the other radio telescope—and nothing happened. Tony and the other supervisor, Paul Scott, started walking down this very long la saying, “Now what is this signal, what’s going on?”, and I tagged along behind trying to keep up with them in every sense of the word. Robin Collins, the other student, had stayed behind with his chart recorders. The discussion continued: “What could show up in our radio telescope but not in yours and has these properties?” Then Robin called out, “Here it is!”, and we went charging back up the lab. We had miscalculated the alignment of the second radio telescope’s beam, fortunately by only five minutes. If it had been half an hour, perhaps we’d have gone home and not found pulsars in Cambridge.

At the center of the Crab Nebula lies the Crab Pulsar — the collapsed core of the exploded star. The Crab Pulsar is a rapidly rotating neutron star — an object only about six miles across, but containing more mass than our Sun. As it rotates at a rate of 30 times per second the Crab Pulsar’s powerful magnetic field sweeps around, accelerating particles, and whipping them out into the nebula at speeds close to that of light.

Our radio telescope and receiver were exonerated. Whatever the signal was, it was common to the radio astronomy site, but it looked like artificial interference. Tony had looked more carefully at its right ascension, and sorted out one of the other problems. We were using an interferometer and interferometers have fringes; or in the case of radio telescopes, negative-going lobes and positive lobes. This signal not only was weak, but also it rarely stayed strong enough for long enough to appear in more than one lobe. So typically you got a short burst of it in one of the lobes within the beam, which meant that its appearance time would jitter around by about 30 seconds. So it keeps constant right ascension—funny for artificial interference. It pulses at a very rapid rate, therefore it’s small. It maintains its pulse period very accurately. Each time we went to observe the thing we found it spot on—absolutely bang on—and we were able to improve the period by another few decimal places. But if something is going to maintain its pulse period very, very accurately, it has great reserves of energy and it must be big. So, it’s big—and it’s small.

So Far Away

Then we started to measure the distance. This was John Pilkington’s job and I can remember him tearing his hair out. Working with a transit instrument is very tricky. If anything goes wrong and you don’t have everything working perfectly for the right five minutes of the day, you’ve lost 24 hours. And this was technically a tricky experiment to do, although it is based on a well-known radio dispersion phenomenon. If there is a thunderstorm in New Zealand with a lightning stroke, that lightning stroke generates a radio signal. It’s a broadband radio signal containing many frequencies, and that signal propagates round to the antipodes, going quite far out from the Earth following lines of the magnetic field, and coming back down in Britain. As it travels that loop of magnetic field it gets dispersed, so what started off as a single sharp broadband signal in New Zealand arrives in Britain sounding like the descending tone of a whistle; a “whistler” to the radio ham. The high frequencies travel faster and arrive first, so you hear a descending note. Similarly in space, the radio signals from stars and galaxies propagate through a space containing free electrons which will disperse a radio signal. So supposing these pulses start out like the lightning stroke as a single sharp broadband signal, by the time they have traveled to Earth they will have become spread out. The amount they are spread out depends on how many electrons they have passed. If we can guess the number of electrons in interstellar space, then we can guess at the distance; that was at the heart of the measurement that John was doing. And he came up with the interesting result that this source was about 65 parsecs, or a couple of hundred light years distant, which puts it way beyond the Earth and solar system, but within our own galaxy—out there among the stars of the Milky Way, in the constellation of Vulpecula. So, after about a month we had established that this thing kept constant right ascension, it was at that sort of distance, that it pulsed extremely accurately, and it pulsed extremely rapidly. And we weren’t at all sure what it was.

There was a meeting just before Christmas 1967 which I stumbled upon. I went down to Tony’s office to ask him something and, unusually, the door was shut. I knocked and a voice said, “Come in.” I stuck my head around the door and Tony said, “Ah, Jocelyn, come in and shut the door.” So I went in and shut the door. It was a discussion between Tony Hewish (my supervisor), Martin Ryle (the head of the Group), and probably John Shakeshaft (one of the other senior members of the Group). The discussion was along the lines of “how do we publish this result?” We only had one of these things. We hadn’t a clue what it was. We had begun nicknaming it “little green men,” although we didn’t seriously believe it was little green men, but it was as good a name as anything else. Up to then we had kept quiet about the phenomenon because we were terrified of making fools of ourselves. What if it turned out to be a thermostat in the next village or something like that? Now we had to publish.

We didn’t solve the problem that night. I went home feeling very fed up. Here was I trying to get a PhD, and some silly lot of little green men had chosen my radio telescope and my frequency to signal to planet Earth. After some supper I came back into the lab because with all the special observations there was by now a backlog of 2500 feet of routine chart analysis. And just before the lab shut at 10 o’clock, I was looking at a patch of sky which included Cassiopeia A, a strong radio source, at lower culmination. It is circumpolar in Britain which means that you can pick it up beautifully in the south and, 12 hours later, if you’re unlucky, it is so strong you can pick it up again in the north, through the back of your radio telescope. Then it is very low on the horizon, it scintillates like fury and it is a mess. I was looking at a record that covered such an observation and indeed it was a mess. In among the mess there seemed to be one of these funny, scruffy little signals. OK, the lab is about to shut and I don’t want to be locked in for the night. Previous records of that part of the sky were pulled out very quickly and strewn over the floor; and there, on two or three previous occasions was a hint of scruff in among that Lower Cas mess. This was 21 December and I was going home for Christmas next day to announce my engagement so it was important I went.

I didn’t go to bed that night. At two o’clock in the morning (the time of transit) I was at the observatory, and it was extremely cold. For reasons that I never understood, when it was very cold the telescope operated at half power. And of course that night it was at half power. So I flicked switches, breathed on it and swore at it, and I got it to work at full power for five minutes. It was the right five minutes and at the right setting. In came another stream of pulses, this time at an inter-
val of one-and-a-quarter seconds, not one-and-a-third. This was a “eureka!” moment, because we’d been through all the tests. It wasn’t a fault with the equipment, it wasn’t locally generated, it was something out there among the stars. Whatever it was, this was another one, in a totally different part of the sky. It nailed the LGM theory as well, because it was highly unlikely that there would be two lots of little green men on opposite sides of the universe both deciding to signal at the same time to a rather inconspicuous star on a rather curious frequency and using a technique that was not at all intelligent. It had to be some new kind of stellar something and we’d found the first ones.

I went off on holiday and came back to the lab wearing an engagement ring. That was the stupidest thing I ever did. In those days, married women did not work. They might work for “pin money” for a little time perhaps, but once the children came along, everybody knew that if mothers worked the children would become delinquents. My appearance wearing an engagement ring signalled that I was exiting from professional life. Incidentally, it is interesting to notice that people were much more willing to congratulate me on my engagement than congratulate me on making a major astrophysical discovery. Society felt that in getting engaged I was doing the right thing for a young woman. In discovering pulsars, I wasn’t.

**AND THEN THERE WERE FOUR...**

During my holiday, Tony had very kindly kept the survey running. He’d put fresh paper in the chart recorder and fresh ink in the inkwells, and piled the charts unanalyzed on my desk. So on my return it was quite clear what I had to do. I began to think I’d had too good a holiday when after about an hour I’d found two more scruffy signals. Tony came by and said, “How many more have you missed? Go back through all your old recordings.” This I dutifully did, but I didn’t discover any more. Over the next couple of weeks we confirmed numbers three and four. Number four was really exciting because it had a period of a quarter of a second, not one-and-a-quarter, and was stretching our understanding. It could also be, on occasion, an incredibly strong signal. It became something of a tourist attraction for other researchers and students, who would go out to the observatory at the appropriate time just to see a pen sweeping across the chart paper and banging against the end stops four times a second.

There was still the puzzle of what these things were. John Baldwin recalled an article from several years back which suggested that maybe in supernovas you could get formed things called neutron stars, and of course we also knew about white dwarfs which are fairly compact. So we composed the paper announcing the first result—and looking back on it were mad. That first paper was based on just one hour of observation in total, but not, of course, an hour continuously. I remember a serious discussion about the title. Was it to be “Pulsating source” or “Pulsed source”? Martin Ryle called up *Nature* and said we’d got something exciting—hold the presses. *Nature* turned the paper round in about a fortnight and it appeared 35 years ago. Shortly before the paper appeared, Tony gave a seminar and announced what we had found. Fred Hoyle said at the end of the seminar, “This is the first I’ve heard of these objects,” but then immediately went on: “I don’t think it’s a white dwarf. I think it’s a supernova remnant.” It shows the caliber of the man and his astrophysical understanding that when presented with something like that, within the hour he could hit the right conclusion. Brilliant! In the paper we had been a bit ambiguous about what we had witnessed because we honestly didn’t know what it was.

There was a lot of publicity following the announcement. The Press descended and when they discovered that S. J. Bell was young and female, they descended even faster. And that was another very interesting experience. Typically, they would ask Tony Hewish about the astrophysical importance of the discovery. And then they’d turn to me and ask me what my vital statistics were or about how many boyfriends I had. I wasn’t shapely enough for page three, but that was all women were for. The science correspondent of the *Daily Telegraph* actually named the objects. He was interviewing us one day and asked us what we were calling these things. We hadn’t considered the matter, so he said: “Well, there are quasars, what about ‘pulsar’ for pulsating radio star?”

Now we know of about 2000. The number is going up rapidly thanks to a survey in Australia. We tend to see the ones in the nearer half of the galaxy, not the farther half because those are too faint, by and large. And we do believe that they are neutron stars—objects dreamed up by some mad theoreticians in the early 1930s shortly after the neutron was discovered! We do believe they are formed in supernovas as Fred Hoyle said, and that they are the core of the star that explodes in the supernova. Neutron stars these days are not only known as radio pulsars, they are one component in many X-ray binaries, they are gamma-ray sources, and they are probably gravitational radiation sources. We believe that what we see as the pulse period is in fact the rotation period; the magnetic axis is offset from the rotation axis, like on Earth only more so. A radio beam comes out of the magnetic pole, and as the star spins you see one flash, or maybe two flashes per revolution. The period is so very precisely maintained because it’s geared to the rotation. Getting a star rotating is hard work but once the star is spinning it is difficult to change the period. We probably only see about one pulsar in five.

So what would a neutron star be like? There’s just over 1.4 solar masses jammed in a 10 km radius sphere. The gravitational field is enormous. The work put into climbing Everest on Earth is comparable to climbing 1 cm on the surface of one of these stars. Even light on the surface is bent by the gravitational field, so you can see tens of degrees over the horizon, and clocks run at half the rate they do on Earth. There’s also a

(continued on next page)
very strong gradient to the gravity so I wouldn’t recommend going to visit a neutron star. The gravitational force on the lower part of your body is so much stronger than on the upper part that “spaghettification” and rupture take place. There’s also some very interesting condensed matter physics. In brief, unlike any other kind of star that is a burning ball of gas, a neutron star is like a raw egg. It’s got a solid shell on the outside and some very funny gooey liquids on the inside. More technically, the shell is believed to be an iron-56 polymer with a Young’s modulus about $10^6$ times that of steel. The very strong magnetic field—about $10^8$ T—makes the atoms in the star aspherical. The iron atoms lock together like tent poles, producing polymers. The polymers stick together and are incredibly strong. Inside the crust is a region rich in neutrons. Elements that are radioactive here on Earth cannot decay in that regime, basically because—decay is prevented. Go a little bit farther and inverse—decay takes place, so protons and electrons merge to give yet more neutrons and it gets even more neutron rich. Inside that is a layer of neutron superfluid or probably two layers, one being $S$ symmetry, the other being $P$ symmetry. The core of the star we honestly aren’t sure about. It may not be the same for all pulsars. Some may be solid, some may be liquid. The Fermi energy is high enough to create bosons so Bose-Einstein condensates are possible. Technically, the Fermi energy is probably high enough to create strange quarks. In short, you have a star 20 km across, weighing the same as the Sun, with immense magnetic and electric fields ($10^8$ T and $10^9$ Vcm$^{-1}$ respectively) spinning on its axis up to several hundred times per second. This is extreme physics.

There is more. The first planets discovered beyond the solar system were orbiting a pulsar. Why there are planets round a pulsar is another question. The roundest known thing in the universe is the orbit of a pulsar round its companion star. It’s round to 1 mm in the radius of the orbit. And if you drop anything on the surface of a neutron star, it hits the deck at half the speed of light. So, these are bizarre objects, hard to believe, but we are forced to believe in them.

**Lessons Learned**

What lessons have we learned? A lot that is politically incorrect in the current research climate! Having one’s own equipment and knowing its foibles is very important. Common-user equipment gives us access to all sorts of things, but the observer doesn’t know the equipment that well. Being a research student is important. I don’t buy into the idea that our brains fade with age, but we do get other responsibilities, and we don’t have the space and time that a research student does. As a student I was not goal-oriented and followed up on things that I could well have ignored—a mere quarter inch in 400 feet. We had moved into a new domain, a new area of phase space, with higher time resolution and more sensitivity. That was important.

Furthermore, we have neglected, incidentally, time-variability. The X-ray astronomers are alert to it, the radio-pulsar people are alert to it; gamma-ray astronomers are too, but only now are the optical astronomers starting to study “things that go bump in the night.” It’s a fascinating and under-researched topic.

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A diagram of a pulsar showing its rotation axis, its magnetic axis, and its magnetic field.

Image from: http://imagine.gsfc.nasa.gov/docs/science/know_l2/pulsars.html