CQ Web Bonus

Digging Deeper with Dr. Joe Taylor, K1JT … on how binary pulsars proved Einstein was right, the communications theory behind WSJT, and the relationship between ham radio and science today.

BY RICH MOSESON,* W2VU

Our interview with Dr. Joe Taylor, K1JT, was published in the October, 2009, issue of *CQ* magazine. Taylor is the James McDonnell Distinguished University Professor of Physics (Emeritus) at Princeton University, a Nobel Laureate and the developer of the WSJT software suite that has revolutionized meteor scatter and moonbounce communications. Our wide-ranging discussion covered so much ground that it was impossible to include everything in the print version of the interview, so here you will find greater detail on some areas of our discussion as we "dig deeper" with K1JT. (We strongly recommend that you read the print version first.) -- W2VU

Growing up on a farm in southern New Jersey, Joe and his older brother, Hal (who also became a ham - K2PT - and is now a Silent Key) discovered ham radio and science at the same time, building stuff out of discarded TV sets and building one antenna support that managed to shear off the chimney of the 1720s farmhouse where they grew up. "It was the base of our tower," he noted, adding, "not a very good design."

In our main interview, Joe explained how his growing interest in science, spurred on by ham radio, led him into a career in radioastronomy, and how his discovery of binary pulsars in 1974 -- along with fellow ham Russell Hulse, then WB2LAV -- led to their sharing the Nobel Prize in Physics in 1993. It was not the discovery itself for which they were honored, Joe noted, but rather for the way they used that discovery to prove a portion of Einstein's theory of relativity. We asked how they did that, and since Joe is a physics professor, we got not only an explanation but a physics lesson at the same time…

K1JT: We could tell right away that the pulsar was unusual (when we discovered it) because the interval between the pulses, instead of being very precisely constant, was very precisely determined but slightly variable in a way that was a dead giveaway to orbital motion. We saw the Doppler shifts in the period between the signals. We recognized that accurate measurement of those Doppler shifts over a period of years would allow us to examine in great detail the gravitational forces holding the pulsar in its orbit. And over the passage of time, we would be able to tell whether the orbit was changing slightly, in its shape and its size.

Relativity theory predicts that an orbit like this one should gradually lose energy in the form of gravitational waves, carrying away some of the orbital motion energy in the form of energy that - according to Einstein's theory - should be generated. Rather like electromagnetic waves are generated by an accelerating charge, gravitational waves are generated by an accelerated mass.

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Dr. Joe Taylor, K1JT, in his office at Princeton University.

Now that is something that was predicted in 1915, when Einstein published his relativity theory, but Einstein himself actually felt that it was rather unlikely that that could ever be tested, because the amount of gravitational wave energy is very small from anything that you could build in the way of a laboratory experiment, and would be totally undetectable in the laboratory.

But nature, of course, is not limited to things that you can build. Nature can make very large objects, like neutron stars with very high mass, very fast velocities, and this system loses enough -- it's still not very much -- but it loses enough energy that we can see a very small change in the size of the orbit over time. It happens that the size of the binary pulsar orbit is about the same as the size of our sun. These are tiny stars. They're made of nuclear material rather than atom-

Poster describing the work for which Taylor and Russell Hulse, ex-WB2ALV, shared the 1993 Nobel Prize in Physics, signed by both men.

ic material, so these two very heavy objects are separated by a diameter about equal to the sun.

CQ: What's the difference between nuclear material and atomic material?

K1JT: Atomic matter is mostly empty. You've got an atomic nucleus and a cloud of electrons around it with a lot of empty space. The analogy that people often use is that it's like the solar system, with a sun in the center with almost all the mass and little planets around it which don't amount to much, but we happen to live on one of them. An atom is like that -- electrons around a nucleus, with mostly empty space in between. And if somehow, you could have only the nuclei, that is, sort of do something that would force the electrons to recombine with the nuclear material so that there's no cloud, just the solid centers, then you would have nuclear matter. And you can't do much of that in the laboratory or on the Earth, but the very strong forces of gravity in the center of a star conceivably can do that, and that's what a neutron star is. It's something which has been compressed under the force of gravity so much that ordinary atomic material can no longer withstand the force of gravity and you end up with only neutrons in the center.

A teaspoonful of neutron star material weighs about a billion tons on Earth, so this stuff is *really* dense, much moreso than any atomic matter would be. And a neutron star spins rapidly because of the conservation of angular momentum. When you make a spinning object shrink, it spins faster and faster. The sun spins about once a month, but if you compressed it to the size of a neutron star, it would be only about 20 miles in diameter and it would spin at 1000 times a second or something. So pulsars typically spin a few times per second, or even a few hundred times per second, and they're strongly magnetized.

A spinning magnet is an electrical generator, so a spinning pulsar generates very strong electrical pulses above its polar regions. Those give rise to sparks and you have essentially a spark transmitter of radio waves, and those radio waves are detectable over interstellar distances. So a spinning neutron star is essentially, you can think of it as one of nature's most precise clocks. It generates radio noise, which is blinked on and off to a fixed observer in the same way that a lighthouse beacon appears to blink because it's rotating around. So every time the beam sweeps over the Earth, we get a pulse. That's why it's called a pulsar, blip, blip, blip, and the timing between those blips is the thing that allows us to measure Doppler shifts.

CQ: Are you still in touch with Russell Hulse?

K1JT: Yeah. In fact, Russ Hulse is here at Princeton; he has been employed at the Princeton Plasma Physics Lab, not a part of the main teaching part of the department, but … up the road a ways, where they are involved in the magnetic fusion effort, in a very big, federally-funded government laboratory. So he's been there… we don't see each other every day or every week by any means, but we do interact a fair bit.

Russ actually retired, officially, I guess it's two years ago now, from his Princeton job, although he still keeps an office there, and he's spending most of his time now at the University of Texas in Dallas in an educational development effort. He's always had a large interest in science education and that's what he's working on now.

Speaking of being officially retired, we noted that Joe himself is officially retired but maintains an office on campus and is still listed on the Physics Department website as supervising a group of graduate students.

K1JT: Actually, you shouldn't believe that too closely. I have not taken on new graduate students starting a Ph.D. for four or five years. It takes about five years to do a Ph.D., and I knew I was going to retire so I sort of stopped that. I'm not still generating a steady stream of new graduates. I stopped lecturing two years ago. I certainly interact with the graduate students here and I go to the weekly seminars and see what the students in my group, my general area, are doing, but I'm not supervising their theses personally any longer.

CQ: I noticed that your group came under the umbrella of the cosmology experiment. What is that?

K1JT: Right now, the principal effort of the astrophysics group is doing cosmology, meaning things that have to do with the large-scale structure of the universe, the Big Bang and how the galaxies, stars, planets and so forth developed after what we now understand to have been, in some sense, the beginning of the present universe.

The NASA experiment known as W-MAP was originally called MAP, the Microwave Anisotropy Probe (*What is anisotropy? See the sidebar, "Ani-What?"* - ed.). That was an experiment designed here at Princeton and built together with faculty and graduate students here and the staff at NASA Goddard Space Flight Center. The "W" was added because my recently deceased colleague, Dave Wilkinson, was the leader of that project and it's now called the Wilkinson Microwave Anisotropy Probe.

They look at the radiation that was actually discovered at Bell Labs in 1965 by Penzias and Wilson, the so-called 3 Kelvin black body radiation that is left over now as a remnant of the Big Bang, essentially, and the WMAP experiment essentially has mapped out that radiation. It's what is the sort of ultimate limit to the sensitivity of any space communication, because it means that even if you build a perfect receiver and point it at cold sky, you never see zero, you see a few Kelvin of noise temperature, and that provides an ultimate limit to sensitivity when you're doing E-M-E or anything else with your antennas - satellite communication -- when your antennas are pointed up. So that's of some interest to hams as well.

The Roots of WSJT

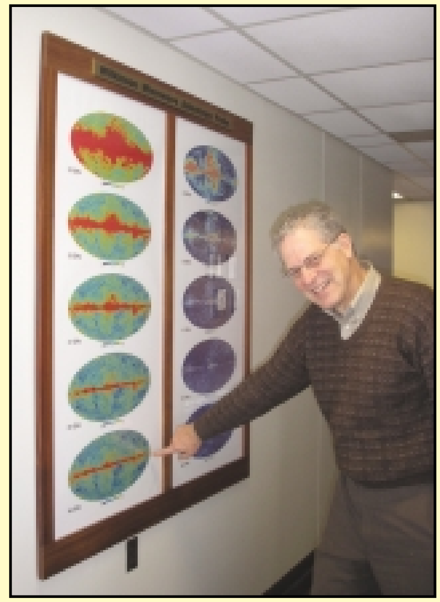
On the topic of E-M-E, or moonbounce, communications, Joe Taylor's WSJT software suite has revolutionized this

Ani-What?

The project that Joe Taylor's research group at Princeton is currently working on is called the Wilkinson Microwave Anisotropy Probe, named for his now-deceased colleague, Professor David Wilkinson. Most of know what microwaves are, but what the heck is "anisotropy" and how do you pronounce it? Well, it's pronounced "an-eye-SAH-tro-pee," and any ham who's ever read antenna specifications will quickly be able to understand what it means.

Antenna gain is often measured in *dBi*, or decibels over *isotropic*. And we've all learned (hopefully) that an isotropic antenna is a theoretical antenna that radiates equally in all directions, with RF radiating out like a bubble. We're also taught that such an antenna can never exist, at least not here on Earth, where buildings, trees and the Earth itself all affect that "perfect" pattern. But in the vast reaches of space, an isotropic pattern is theoretically possible, and when Arno Penzias and Robert Wilson discovered (in 1964) the cosmic background radiation believed to be left over from the "Big Bang," it was believed that that radiation was indeed isotropic, at an equal level wherever you looked in the sky. But subsequent research and advancing technology have shown occasional variations in the cosmic background radiation – meaning it is not totally isotropic, but an-isotropic in places. These points of *anisotropy*, which the WMAP project is working to map, are now believed to have been the starting points of star formation, leading to the growth of the universe as we know it today. There, now you can talk like an astrophysicist, too!

The Wilkinson Microwave Anisotropy Probe (WMAP), a joint NASA/Princeton mission to explore the origins of stars and galaxies, with which Dr. Taylor and his graduate students have been heavily involved.



K1JT points out one of the images from WMAP showing a "bump" in the cosmic background radiation that might suggest the starting point of a star or galaxy.

mode, making it accessible to VHF stations with 100 watts and a single Yagi, as opposed to the superstations that were required in the past. In addition, WSJT has made meteor scatter communications possible for virtually any ham with a VHF SSB or CW transceiver. Joe said it all started as an effort on his part to learn more about communication theory and apply some of that knowledge to ham radio…

K1JT: Communication theory is a pretty young subject. I mentioned *(in the main interview - ed.)* that radio astronomy was young when I got into it in the 1960s. Communication theory started at about that same time. The classical papers that are always referred to are by Claude Shannon, a man at Bell Laboratories here in New Jersey, and the papers which came out in 1948, right after the war. He was then looking at the details of what was necessary in a mathematical sense to guarantee that you can convey information from one spot to another with a certain amount of power available, and a certain signal-to-noise ratio, with a specified error rate. Obviously, those kinds of ideas are very fundamentally involved in our cellphone technology today, in building disk drives … sending e-mails … (and) any other thing where you want to transfer information from one place to another with a guaranteed very low error rate.

Radio astronomy, of course, is the passive use of radio channels for picking up information from cosmological objects, if you like, rather than transferring manmade signals from one place to another. But at least on the receiving end, the problems are similar and the way in which you deal with signals when they become very weak in, for instance, recovering the digital datastreams sent back to earth from NASA spacecraft as they fly out in the outer part of the solar system. And that's a system which very strongly depends upon the communication theory details worked out by Shannon and others, going back into the '50s. NASA wanted to get those pictures back without any errors, any pixels missing, and things like that. So they use Reed-Solomon codes and convolutional codes and all these other things. I was sort of aware of that but didn't know the details of how it worked and when I said I wanted an excuse to learn those things, I wanted to find a way to learn that and, by the way, have some fun applying it to ham radio…

So in 2000, I started working on schemes that would allow us to do meteor scatter and then moonbounce, using some digital signal processing. Computers were by that time getting ubiquitous and cheap and many hams had them, and I realized that if the right software were available, it would be possible to do meteor scatter with digital modulation techniques with otherwise regular ham radio equipment, and it would be much more efficient and much more easy to complete contacts by meteor scatter with these kinds of techniques than it would be with CW or single sideband. And then I realized that the same sort of thing could be done with moonbounce as well…

Now a moonbounce contact is not a good time to do any ragchewing. You're basically going to exchange callsigns and a signal report and probably not much else. You might say 'good morning, Jack' or something, but you're not going to exchange a lot of information. So the WSJT moonbounce modes allow you to send callsigns and your grid locator and a signal report and - if you want to chit-chat a little bit, you can also do that - but the maximum message that you can transfer in a single transmission, which lasts for one minute, is 13 characters. So anything you can say in 13 characters, you can say on WSJT!

CQ: It takes a full minute to transmit the 13 characters? Does it send it just once?

K1JT: What it actually sends is a very carefully crafted message of 378 bits, which are redundant by a ratio of about 6:1. There are actually 72 digital bits, 72 zeroes and ones, that convey the information. Now 72 bits at 6 bits per character would be 12 characters, and in fact, I don't need quite 6 bits per character, I need only about 5.4 or something, so that's where the 13 characters comes in. But there's some more … I mean the reason for high redundancy, you send 378 bits but you really only want to recover a message of 72 bits, that high redundancy has got a lot of mathematical sophistication built into it.

It's a so-called Reed-Solomon code. It's the same kinds of error-correcting codes that are used in audio CD-ROMs, in disk drives in your computer, it's why your computer virtually never forgets anything that's on its disk unless the whole disk crashes or something. When you read back a file that you had recorded on a disk, you get back the file exactly, with no errors.

We know that recording mechanisms can't be error-free, but you can make them very close to error-free if you build in a sufficient amount of redundancy in the way that the data are recorded. And that same kind of sophistication is built into the codes that are used in WSJT. The mode used for moonbounce is called JT-65. The number refers to the fact that uses 65 tones of frequency shift keying. One of those tones is for synchronizing and the other 64 tones convey data. The synchronizing establishes the frequency and time offsets between the two stations very accurately, and then the data tones can be decoded from that.

CQ: Considering the time delay involved, how does the coordination work?

K1JT: That's a good question. Both operators have to have their computer clocks set to WWV or some internet time standard so that they are correct to within a second or so. The time delay for a signal traveling to the moon and back is about 2-1/2 seconds, so the receiving software knows about the expected time delay of 2-1/2 seconds; it knows that my computer or the other guy's computer might be inaccurate in its clock by a second or so. And therefore it has to search over a range of about 5 seconds, looking for the appropriate synchronization. It knows there should be about a 2-1/2 second delay but there'll be a plus or minus of a couple of seconds of error, so it basically searches over that whole range for this synchronizing tone, and of course it also searches over frequency space, because even though the other guy and I may have agreed that we're going to meet on such and such a frequency at a certain time for a sked, his radio and mine may both have some calibration inaccuracies.

There's also a Doppler shift involved in the EME path, so it has to search over some range of frequency as well. And it does that, again, by looking for that synchronizing tone. So the sync tone allows you to sync up in both time and frequency, time to within a fraction of a second, and frequency to within a few Hertz. And then it can look for the data tones and try to dig those out of the noise.

K1JT in his ham shack at home.

Digging those signals out of the noise is where these techniques have carried over from my pulsar studies into ham radio. I guess the point I was starting to make a minute ago was that because of the Reed-Solomon code used in the JT-65 protocol, when the receiving station recovers a message, essentially always, the message will be exactly what was transmitted, or else the decoder will simply say 'I didn't get it.' You either get the message exactly or you don't get it at all. If you don't get it at all, you have to transmit again, and there is an averaging mechanism built into the program so that if the signals are too weak to recover a single minute's transmission, you can average successive minutes, you know, five, ten, fifteen minutes even, and it'll eventually decode the signal. So that's another way of getting down even deeper into the noise level…

And the WSPR mode (*which tracks propagation openings - see main interview. - ed.*), by the way, has this very strong forward error correction, FEC ... I used a Reed-Solomon code in JT-65 but the WSPR mode uses a so-called convolutional code instead. It's a different mathematics, and it's better-suited to modulation with a few tones rather than a large number of tones like the 65 tones that are used in JT-65. So the WSPR mode actually only uses four tones, two tones for synchronizing and the other two tones for data, and that matches very well with the capability of a convolutional code.

The Big Picture…

Finally, we asked Joe what he sees -- from his perspective as both a scientist and a ham -- about how the relationship between the two has (and has not) changed over the years, and about perceptions of science in society today.

K1JT: It was great that in the 1950s and early 60s, when you took apart a television set of those times, you basically could make out what everything was and what it did. Even the vacuum tubes -- we actually used to take a couple of the tubes that we knew we were not going to be able to use, wrap them in a towel or something and tap them gently with a hammer so that we could get the glass off and then take them apart, and you know, you could actually see that, here's the filament, here's the grid, here's the plate. This must be how it works. This was great. You can't do that with modern solid-state electronics but, and of course, you can't open up your automobile engine and see how it works the way we could in those days, either. That was, I think, I *know*, was one of the things that used to make it fairly easy for kids who were technically inclined to learn enough to get them started. You have to do it different ways today.

CQ: What are some of the different ways that you see?

K1JT: Well, I think that one of the reasons that is always given for it being more difficult to get kids into ham radio these days is that they play with computers instead. Basically the same kind of kids that I think I was. Of course, there's nothing incompatible between that kind of technology and the kinds that we now use in ham radio as well, so I've been encouraging kids that I know that are into that kind of thing to do both.

By all means, learn about computers - those are fascinating, they are a very central part of today's economy and commerce, but so is radio frequency electronics, with your wireless iPhones and everything else. And if you are interested in those sorts of things as a youngster and would like to learn more about them, a very good way to do that is to get yourself involved in this hobby of amateur radio.

It's still quite possible to build crystal sets, as we did, and it's very exciting to put together just a very small handful of parts and an earphone and run a wire out to a tree and pick up a radio signal, and once you've done that, you can discover that there are more complicated things you can do as well, and that often turns on a kid…

When I was a graduate student, if I was in a group, say at a scientific meeting with five or six radio astronomers present, typically half of them would be, would have ham licenses. That's less true today, but I think it's less true largely because of the phenomenon I mentioned earlier that means kids who are interested in technical things are much more likely to be computer-savvy these days than RF electronics savvy. We still get some of it in ham radio, and I definitely see the evidence of cross-pollination between the amateur interests and what become professional interests for some young developing scientists…

I fear that there has been, across the country, in at least a portion of the population, a kind of anti-intellectual, anti-learning, sort of undercurrent in recent years. I would like to see that reversed. I would hope that the government can do things to somehow, not only improve the educational system but somehow improve the attitude toward what can be gained, what benefits are available to us if we can generate learning in all areas that will improve our economic competitiveness and be better for the overall well-being of the country.