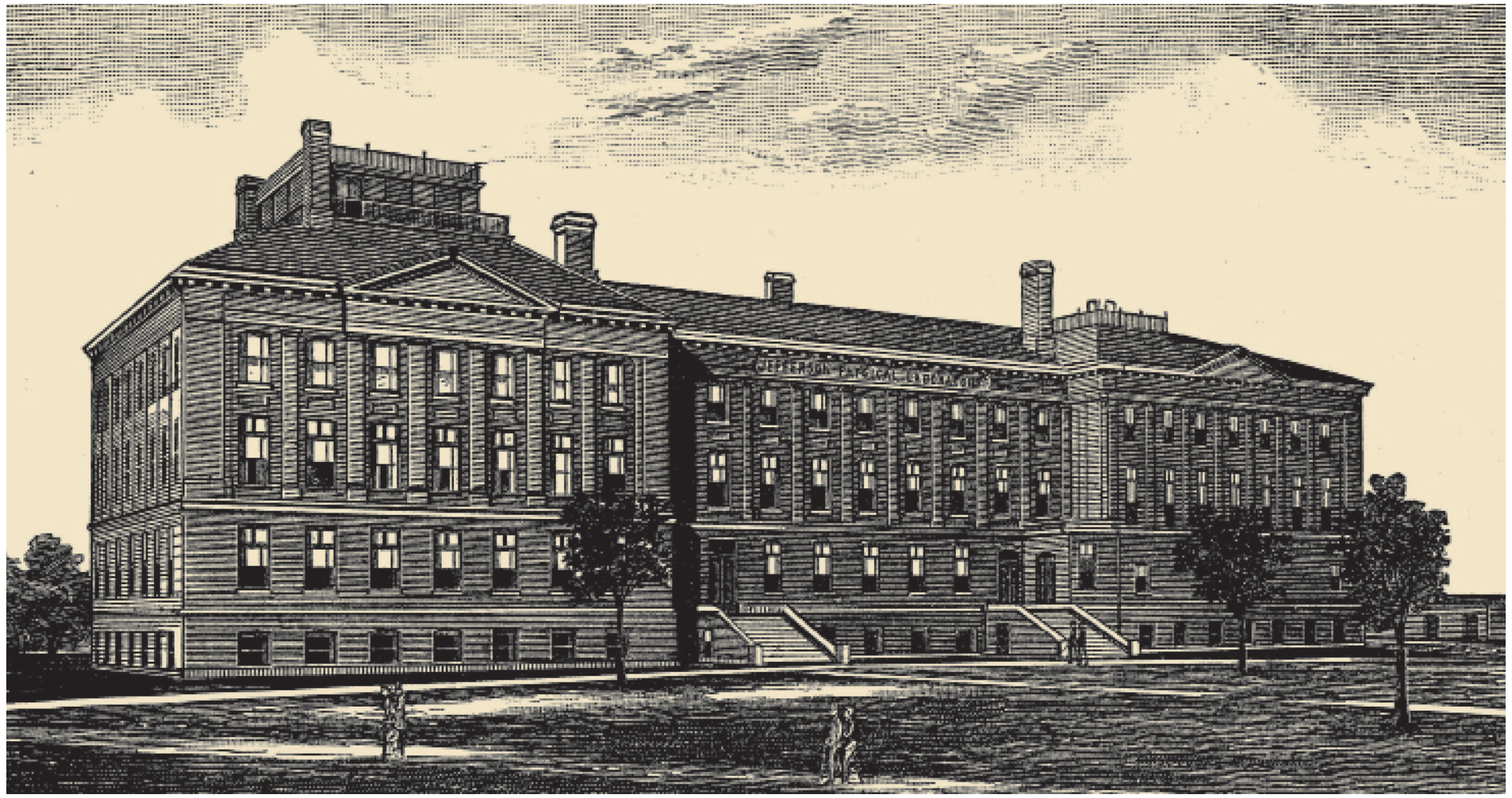

HISTORICAL FOCUS

RADIOASTRONOMY'S FIRST SPECTRAL LINE: "A Glimpse of the Handiwork of Creation"[1]

by Paul Horowitz

It was 3AM on Easter morning, 1951, when Harold ("Doc") Ewen, working in Lyman 447, telephoned Harvard's Observatory (trusting that astronomers work at night) with the question "can you tell me Earth's velocity vector looking due south, because I'm trying to measure a Doppler shift?" The very short conversation continued "Who are you?" "Physics Department, Harvard." "What are you looking at?" "Interstellar gas. I'm looking at a resonance in interstellar gas and I need a Doppler component from you fellows." "Well, you better call us some other time. *Doppler!*, what are you guys doing over there? *Is this a prank call?!*"

[1] Quotation from Buderi, R., see References.

Figure 1: Harold "Doc" Ewen provides scale for the 1420MHz horn antenna, made from copper-clad plywood, on the parapet outside Lyman 4th floor. The canvas cover was added after the horn funneled a rainstorm into the lab (which Ewen remarked was his first "signal from space").

It wasn't, and, using equipment transported in a wheelbarrow on weekends from the Cyclotron Lab,[2] Ed Purcell's student Ewen had detected the faint whisper of neutral atomic hydrogen in the galaxy, the first radio line emission from space, "a potent probe of the interstellar medium" which "enabled radio astronomers to deduce for the first time a picture of the spiral structure of the galaxy," and "a tool allowing access to two regions previously little explored: the neutral regions of interstellar space and the distant regions of the Milky Way."[3]

The discovery of the "21cm line" is a story of the right people in the right place at the right time. It starts in 1945 with Hendrik C. van de Hulst, a student of Jan H. Oort's in war-torn Netherlands; Oort knew about Grote Reber's backyard radio astronomy (of galactic continuum radiation) from a smuggled issue of the *Astrophysical Journal,* and immediately realized the importance of a possible *spectral line* emission, which would allow Doppler measurements of galactic rotation and structure. Oort set his student the task of identifying candidate spectral features; van de Hulst looked at some high-level electron transitions, but settled finally on the hyperfine (spin flip) transition at 1,420MHz, though pessimistic that it could be detected (he did allow in his 1945 paper that "this possibility does not appear hopeless"). The story moves next to America, where van de Hulst (spending a year at Yerkes Observatory) spoke with Reber about a search. Reber later mentioned it in a 1947 review co-authored with Jesse Greenstein; when Iosif Shklovsky (in the Soviet Union) read the review, he remarked, "It set me on fire," and his subsequent calculations led him to believe that it *could* be detected. Shklovsky concluded his 1949 article with a rousing "Soviet radio physicists and astronomers should endeavor to solve this intriguing and important problem."[4]

The story resumes one year later, when we find Ewen working full-time at the Harvard Cyclotron, in a race with Fermi's group in Chicago to create an external proton beam (Fermi lost!). Ewen approaches Purcell, seeking a thesis topic that combines his interest in physics, astronomy, electronics, microwaves, radar, and meteorology, with the idea of mapping atmospheric 1.25cm radiation. Purcell was unenthusiastic: "It would just be another point on a curve that had been done." Then, after Purcell learned about van de Hulst's work, he remarked "I thought of you when I saw it because that's got to be a lot better than doing a water line in the atmosphere. If you can get a gas line in interstellar space, you'd get your face in *Life Magazine*[5] and no one would ever forget you. And if you don't, you've only wasted a couple years of your life."

[2] As Ewen related, "Most of that equipment was provided on 'weekend loan' by the Nuclear Lab. I would bring it over to Jefferson in a wheelbarrow on Friday afternoon, and then back to Nuclear the first thing on Monday morning. Weekend holidays were cherished. Our payoff weekend was Easter."

[3] Quotations are from Bernard F. Burke, An Introduction to Radio Astronomy (Cambridge Univ. Press, 1997), John D. Kraus, Radio Astronomy, 2nd ed., (Cygnus Quasar Books, 1986), and Woodruff T. Sullivan, Cosmic Noise, A History of Early Radio Astronomy, (Cambridge Univ. Press, 2009), respectively.

[4] Shklovsky interested Victor Vitkevich (a leading Soviet radioastronomer) in the project, but Vitkevich, discouraged by his father-in-law Lev Landau's view of the project as "pathological," didn't follow up.

[5] He did—in 1952!

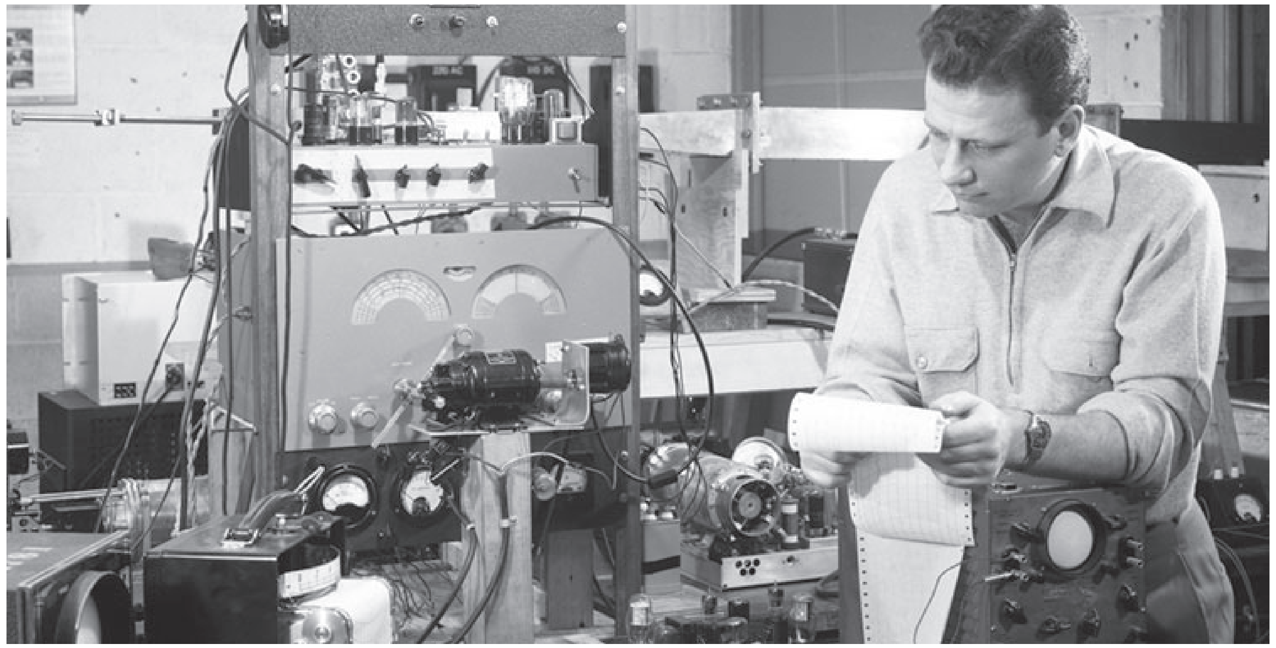

Figure 2. Ewen and the microwave receiver that first detected 21cm radiation from galactic hydrogen. The tapered waveguide behind Ewen's head carries signals from the horn of Fig. 1 to the frontend mixer. The black geared motor at center slowly scanned the National Radio NBS-3 communications receiver, modified for expanded IF bandwidth and 75kHz frequency switching (in conjunction with the lock-in amplifier (see Fig. 3) just above it. The jet-engine shaped object to its lower right is a 3C22 lighthouse-tube radar jammer, pressed into service as a stable first local-oscillator in this double-conversion superheterodyne system. The slow (60-sec time constant) lock-in amplifier's output was charted on the Esterline-Angus strip-chart recorder at left, generating 30-foot-long recordings as Earth's rotation carried the galaxy through the antenna's lobe pattern.

Here's where a confluence of factors came together: from Purcell and Pound's wartime radar work at the MIT Radiation Lab ("Radlab"), there was local expertise in microwave feeds, waveguides, mixers, and microwave oscillators, as well as abundant surplus apparatus; and at the Cyclotron Lab there was an array of quality electronic instrumentation. Furthermore, Purcell, knowing of Robert Dicke's hot-load synchronous detection ("Dicke switching") for *continuum* radiometry, suggested using it in a frequency-switched mode for *spectral* line astronomical detection (analogous to its use in NMR).

It gets better: Purcell sent Ewen down to Bell Labs to learn about a recent technique in calibrated microwave noise sources (anticipating a null detection, thus requiring accurate limits on sensitivity). While there, Ewen visited Harald Friis, who, evidently forewarned by Purcell, greets him with "I've been waiting for an occasion like this to give some kid two of the best crystals ever made by Bell Laboratories. These are beautiful." And Purcell knew of the recent precision laboratory measurement of the hyperfine frequency (1420.4051MHz) by A. G. Prodell and P. Kusch at Columbia, giving confidence in the frequency to be searched.

With a $500 grant from the Rumford Foundation,[6] Ewen built a horn antenna (simpler than a dish, and superior in sidelobe suppression) from plywood lined with copper sheet (Fig.1), and a scaled-up waveguide mixer from Pound's design,[7] with the precious Bell Labs 1N21B diodes. For the local oscillator he used a surplus AN/APT-5 radar jammer, which exhibited surprisingly good (~few parts per million) stability when placed on cushions of cotton wool and powered from a regulated dc power supply (invented by our own Frederick Hunt and Roger Hickman[8] in 1939). The low-noise frontend used the remarkable cascode configuration (invented by the same Hunt and Hickman duo, in the same article!), followed by a communications receiver as "IF amplifier" (modified for frequency switching) and an integrating lock-in detector designed by Ewen. In the style of the time, he used an Esterline-Angus paper strip-chart recorder to plot the smoothed (60 sec RC time constant) trace of the differentiated[9] received power. Figure 2 shows "radioastronomy circa 1951."

After months of moonlighting weekends, Ewen, having tuned up his apparatus to perfection, had failed to detect galactic radiation. He suspected that the signal, if it was there, was so broadened in frequency that his modest 10kHz (by then increased to 25kHz) switching was not enough to take him clear of the line and allow detection. Here we let him continue:

"So then, we had a summit meeting with Ed. As I recall it was in the late fall of 1950 and it was, 'Are we ready to go for the negative thesis?' And Purcell was just a giant at those meetings. Rather than discuss whether it was time to go for a negative result, he was more upbeat: 'Is there anything else that you would like to buy or try before you let it go down the drain?' And I said, 'Well, there was just one other thing I could try in order to separate the frequencies even further but to do it I would have to buy a very expensive new receiver. There was a new one which National Company had just come out with and it costs $300. I would modify that and if that didn't work, nothing would work. But we don't have that kind of money because we only had $500 for the program, and we'd spent that on the horn.' So he said, 'Well, if that is your decision, come on back tomorrow and we'll finalize it.' So I came in the next day (and this is one of the things that he has never given me an answer as to how this happened), and he said: 'Now you're sure—$300 and you buy that receiver and that's going to be it?' He reached and pulled out his wallet and took out $300. I don't know where the $300 [$2,975 in 2020 dollars] came from. It was cash."

Ewen later knew well that his advisor was his benefactor; and, with the new receiver in hand, he tore into it, added a reactance modulator to broaden the switching to 75kHz, and correspondingly the IF bandwidth. And the rest is history: the Easter Sunday run caught the whisper of the cosmos, seen nicely in Figure 4, an observation taken just two weeks later. Ewen may have set a record for thesis writing (energized by being called up for service in the Korean conflict), claiming he wrote the 47-page thesis in three days (and, likely, nights); he submitted it the very next month, and defended in May.[10]

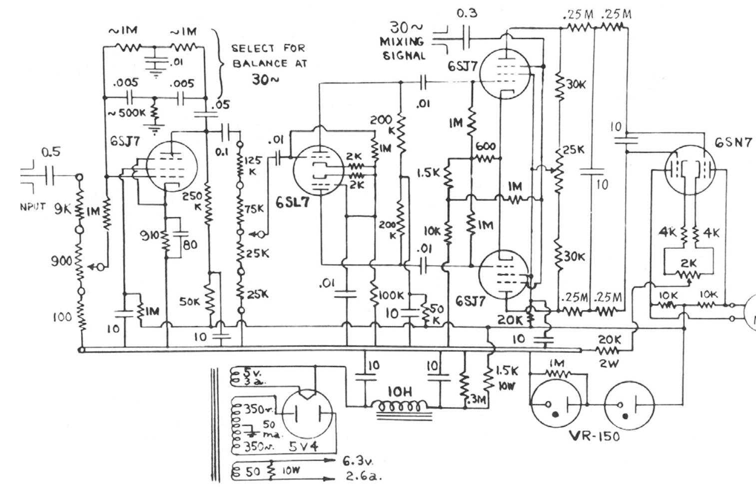

Figure 3: Nowadays you just *buy* a lock-in amplifier, or do the equivalent thing with software operating on digitized data. But in 1950 you built your own equipment, as Ewen did with his 8-tube circuit (from his thesis). Circuit mavens will raise an eyebrow at the component values of the two-stage RC low-pass filter preceding the 6SN7 differential output stage.

[6] See Kleppner, D., and P. Horowitz, "A Perfect Proposal," *Physics Today* 69 (2016).

[7] Pound became Ewen's advisor, with Purcell often away on government work.

[8] F. V. Hunt and R. W. Hickman, "On Electronic Voltage Stabilizers," Rev. Sci. Ins., 10, pp. 6-19 (1939).

[9] Caused by the synchronous "lock-in" technique of frequency-switched differencing.

[10] At the thesis defense, reports Ewen, "after I had been asked a couple of relatively simple questions in physics, the meeting broke up with Purcell and van de Hulst at the blackboard for about two hours to discuss what this all meant from the physics and astronomy standpoint. And I can recall sitting there ... and listening to those giants with my feet up on the chair, until at some point in time Purcell looked around and said 'Oh, you're all set Doc, you can run along.'" But a fuller understanding came only later. As Ewen related, "I can remember a lot of discussions occurred after the detection with Purcell and van de Hulst, trying to figure out what the devil is the mechanism. And it was only about three months later, at one of these afternoon... seminars, that Purcell was describing ... how they were struggling with the physics of possibly the collision hypothesis, that Norm Ramsey and Weisskopf were sitting in the back of the room making so much noise talking to each other that finally Purcell said 'If you have something to say that you can share with us, we'd be happy to hear you.' And Ramsey says, 'We think we've figured it out for you! We've got it all figured.' So Weisskopf, in his usual style, says, 'It's obvious. You have two atoms approaching each other. You form a hydrogen molecule. At the moment of collision, the girl you brought to the dance is no more distinguishable than the other. And so when the collision is over, it'll be just a quick collision, you might take the wrong partner home, and if you do...' That's how it happened. When the molecule, it comes in with one of them antiparallel and parallel, whatever, and then they swap, and once they swap, bingo."

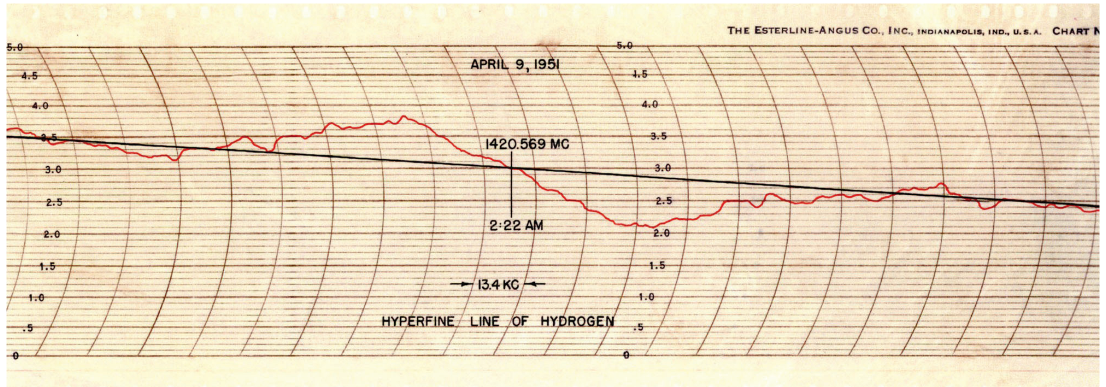

Figure 4: The galactic hydrogen emission signal at 1420MHz (21cm), as traced in red on the strip-chart recorder two weeks after its discovery. The frequency-switched modulation technique causes the trace to have a differentiated S-shape. The sloping black line approximates the receiver's drift over the 20-minute observation. (Reproduced from Figure 18 of Ewen's 1951 thesis.)

Ewen and Purcell submitted their one-page discovery paper[11] to *Nature* on June 14th; but if you look up that volume, you'll find it published in September, followed immediately by confirming papers by the Dutch and Australian groups. That is because Purcell, in a most gentlemanly gesture, asked the editors of *Nature* to delay publication until those groups had time to confirm the discovery and make additional contributions. As explained by Sullivan, "This seemed natural to him since on the one side the Dutch appeared so close to a detection (and in some ways 'deserved' one); and on the other Bowen, chief of the [Australian] Radiophysics Lab, was a wartime crony from Radiation Lab days."

The 21cm discovery energized radio astronomy, and, with the enthusiastic support of Bart Bok, brought Harvard into the field; five years later we had our own 60ft telescope (Fig. 5), and an astronomy department that would not hang up on a phone call at 2AM.

Epilogue

Ewen, a man of many talents, went on to found the Ewen-Knight Corporation, designing and manufacturing instrumentation for radio astronomy. His earlier exploits had included a stint teaching celestial navigation to Navy recruits. Later one of those students visited Harvard; as Purcell relates: "As it happened, various members of the Boston Red Sox were friends of his who had been in the Naval and Marine Air Force. Ted Williams once visited the lab here and came over with Doc. Everybody was all aflutter."

Ewen and Purcell's "line" continues to inform; according to NRAO scientist Ken Kellermann, "The detection of the 21cm hydrogen line proved to be a valuable tool to study galactic dynamics. In particular, the existence of dark matter was dramatically demonstrated by 21cm observations in the 1970s that showed huge increasing mass-to-light ratios in the outer parts of galaxies, far beyond the region accessible to optical studies."

On a more speculative subject, the discovery encouraged activity in SETI (the Search for ExtraTerrestrial Intelligence), for example the 1959 proposal by Cocconi and Morrison to search at 1,420MHz.[12] And Frank Drake's pioneering SETI in 1960 elicited these remarks from Purcell in his Brookhaven talk ("Radioastronomy and Communication Through Space") the same year:

[11] P Ewen, H. I. and E. M. Purcell, "Observation of a line in the galactic radio spectrum," *Nature*, 168, p. 356 (1951).

[12] Their article ends: "At what frequency shall we look? ... just in the most favoured radio region there lies a unique, objective standard of frequency, which must be known to every observer in the universe: the outstanding radio emission line at 1,420Mc./s. (λ=21cm) of neutral hydrogen. It is reasonable to expect that sensitive receivers for this frequency will be made at an early stage of the development of radio-astronomy. That would be the expectation of the operators of the assumed source, and the present state of terrestrial instruments indeed justifies the expectation. Therefore we think it most promising to search in the neighborhood of 1,420Mc./s."

Figure 5: Ewen and Purcell at the 1956 inauguration of Harvard's 60ft radiotelescope at Agassiz Station in Harvard, Massachusetts. Their discovery horn, shorn of its innovative electronics, was hauled out of storage to serve as decorative trapping for the occasion.

"Of course, the exchange, the conversation, has the peculiar feature of built-in delay. You get your answer back decades later. But you are sure to get it. It gives your children something to live for and look forward to. […] Here one has the ultimate in philosophical discourse—all you can do is exchange ideas, but you can do that to your heart's content. … a listening program on a very modest scale is going on at Green Bank under Frank Drake, who has some very imaginative and, I think, sound ideas on how it should be done. They haven't heard anything yet."

References

Unless otherwise cited, quotations come from the following sources:

- Oral histories of Ewen and Purcell https://www.aip.org/history-programs/niels-bohr-library/oral-histories/.
- Woodruff Sullivan's oral interviews https://www.nrao.edu/archives/Ewen/ewen.shtml.
- Kellermann, K. I., E. N. Bouton, and S. S. Brandt, *Open Skies: The National Radio Astronomy Observatory and Its Impact on US Radio Astronomy,* Springer, 2020.
- Buderi, R., *The Invention that Changed the World*, Touchstone, 1996.

- Figures 1 and 2 were scanned by the author from the original 13x18cm Cruft Laboratory negative, and Figure 5 was scanned from a monochrome print in the Agassiz Station scrapbook.