# The Discovery of Interstellar CO

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*Abstract*—**Bell Labs was an early developer of millimeter-wave technology. At the peak of its development there, Arno Penzias, Keith Jefferts and I were privileged to use it to discover CO in what turned out to be star forming interstellar clouds. Interest in mm and sub-mm wave astronomy has blossomed since.**

## I. INTRODUCTION

Prior to 1970, the idea of massive molecular regions in the interstellar medium (ISM) was not in the general consciousness, even though Solomon & Wickramasinghe [1] showed that dense clouds with a hydrogen density n > 100cm−3 would all be molecular clouds with molecular hydrogen H2 as the dominant constituent and very little atomic hydrogen HI. Interstellar CH and CN [2] and CH+ [3] had been known in diffuse clouds from their optical absorption lines since the late 1930s. In a talk in 1955, Charles Townes [4] suggested radio astronomers should look for a number of transitions in simple molecules, including OH, NH3, H2O and CO. In 1963 Sander Weinreb [5] detected OH as the second significant radio line. In 1968 and 1969, ammonia [6], water [7], and formaldehyde [8] were found, but none of these pointed to extensive molecular clouds.

## II. RADIO RESEARCH AT HOLMDEL

In the 1920's Bell Labs saw an increasing need for radio in communications and, in order to escape the electrical noise in New York City set up field stations in New Jersey which were eventually consolidated in Holmdel, NJ. The initial emphasis was using HF radio for transatlantic communications. One famous result of this work was Karl Jansky's discovery that one component of the interfering noise on such circuits originated in the center of our Milky Way galaxy; this started the field of radio astronomy.

This line of research into free space radio communications continued into the 1990's with several accomplishments as higher frequencies were pursued. Starting after WWII, a microwave relay system was developed and was the first nationwide distribution system for television in the US as well as much of the backbone for telephone communications. Work to increase the capabilities of the terrestrial microwave relay system continued for years. In the mid 1950's John Pierce, a Bell Labs polymath, manager and also a writer of science fiction, recognized that satellites would offer an attractive means of communication and, after Sputnik's launch, pushed to exploit them. The Holmdel group hired two young radio astronomers, Arno Penzias and me to aid in that effort with the promise that we could spend half of our time on radio astronomy. While preparing for one of our initial experiments, we discovered the Cosmic Microwave Background Radiation (CMBR). Later propagation of radio waves in cities and houses was studied for mobile communications.

A second line of research had been started at Holmdel when George Southworth transferred there to pursue his interest in guided waves.

## III. PRIOR MILLIMETER-WAVE WORK AT CRAWFORD HILL

In 1932 George Southworth of AT&T demonstrated the first propagation through a waveguide. The next year, Mead at AT&T and Schelkunoff at Bell Labs separately calculated the attenuation of various modes in waveguide—and both discovered quite unexpectedly that the circular electric modes (TE01 is the lowest) have losses which decrease rapidly with higher frequencies in a given circular waveguide. In 1934 Southworth moved to Bell Labs, Holmdel (where Karl Jan-sky worked) to continue exploring waveguides. That same year Russell Ohl used a spark source to investigate millimeter-wave detectors. The Holmdel group's charter was research on long distance communication, and they were constantly pushing technology to higher frequencies to get more bandwidth. The idea of using the TE01 mode in a highly overmoded waveguide for long distance communication was thoroughly implanted in their thinking early and, as millimeter-wave technology was developed, they worked on it with such a system in mind. By 1963, the year I joined the group in the newly completed Crawford Hill Lab, a system was under intense development using a two-inch diameter waveguide with a potential band extending from 38 to 120 GHz. By 1975, a separate development group had built enough of the system to show that coast to coast communication through waveguide was possible. But the capacity was not yet needed—and optical fibers were on the horizon—so the effort was dropped.

Along the way in the mid 1950's, Doug Ring constructed two 8.5 mm radiometers on a military contract. He had a complete truck mounted system for scanning the environment and making 8.5 mm thermal images. His radiometer used a switch made in circular waveguide with a rotating half-wave section. I made a similar switch for the 7 cm radiometer Arno and I used for discovering the CMBR.

## IV. The Discovery of CO in Interstellar Clouds

After the initial excitement of discovering the CMBR had died down, our lab director called Arno and me in and reminded us that the initial agreement had been that we would each spend half time on astronomy and the other half on work for the Bell System and it was time to do some of the latter. We each took on communications projects and our centimeter wave astronomy work slowed down. Arno, however, was doing some observations at the National Radio Astronomy Observatory and made the connection that they had constructed the 36 foot antenna on Kitt Peak for observations at millimeter wavelengths, but Charlie Burrus in the millimeter waveguide group at Crawford Hill was able to make better millimeter wave receivers than NRAO could. Charlie had devised a scheme of using the crude photolithography of the day to make arrays of Schottky barrier diodes on a GaAs wafer. They were mounted in “Sharpless wafers” and the “cats whisker” had only to contact one of the premade diodes, rather than forming a junction at the contact.

The initial 1968 experiment demonstrated the feasibility of this effort, but produced little in the way of new science. We left that 90-GHz receiver for NRAO to use in developing the antenna. Two years later Sandy Weinreb of NRAO offered to provide a spectrometer and frequency control equipment for the 36 ft. We returned with a higher frequency Burrus receiver. Arno talked Keith Jefferts (a Bell Labs atomic physicist interested in millimeter-wave spectroscopy) and me into integrating the Bell Labs receiver into an NRAO receiver box that would fit at the focus of the 36-ft antenna. We would then go back to look for carbon monoxide in interstellar space. At one point in this process, Keith remarked that Arno had the two best technicians at Bell Labs wiring the receiver for him.

The payback came when Keith and I joined Sandy at Kitt Peak to get it all working. After several frustrating days, Sandy had to leave, but the next day we got it all tenuously working and put it on the antenna. I asked the telescope operator to point to the BN/KL region of the Orion Nebula where two bright nebulae, one in the near infrared and the other in the far infrared, would be in our beam. I was watching the rather crude output of the spectrometer when some of the center channels increased from their somewhat random previous outputs. The operator confirmed that we had just reached the source. I asked him to go off the source and the channels went back down. Thus in a few seconds, using a system which was hundreds of times less sensitive than the one on the 20-ft horn-reflector, we discovered carbon monoxide in an interstellar cloud. I had picked the BN/KL source because it was the source in our list of candidates that was overhead at the time, but it turned out that it is the strongest CO source in the sky. Arno arrived the next day to find that the key discovery had been made [9].

The carbon monoxide and other simple molecules that we and others have found since can be thought of as stains which allow us to measure the structure and dynamics of the interstellar molecular clouds. The clouds are so cold that their main constituent, hydrogen, doesn’t radiate. The radiation from simple molecules has shown that these dense molecular clouds exist, star formation is active in them and they are common in galaxies. Since that time, a large number of astronomers have worked on understanding the physical and chemical conditions in these clouds and the formation of stars within them. For several years after the discovery, Bell Labs gave Burrus diodes to other observatories and taught other groups how to make them.

This discovery changed the direction of my career. We spent five exhilarating years exploring interstellar clouds and discovering new molecules and their isotopic variants with our receivers and the 36-ft antenna at Kitt Peak. We had the only receivers above 100 GHz for several years, so we were pretty much free to follow the leads we saw and observe what we wanted to. That contributed to rapid advances. We had a lot of instant gratification with new sources, new molecules, or new insights from every observing run.

I then became project director for the 7-m antenna. It was designed to do millimeter-wave astronomy when the weather was good and satellite propagation measurements at 1-cm and 2-cm wavelengths in weather bad enough to affect those bands. We then had almost two decades of additional studies of molecular clouds and the cores around young stars which are embedded in them. The Crawford Hill astronomy group grew to include several additional people at its peak. Later the astronomy effort became less relevant to AT&T’s need to prosper in the post-divestiture days and therefore declined. The Sub-Millimeter Array which I am working on now is an aperture synthesis array that spends most of its time observing radiation from the simple molecules and dust in these star-forming regions.

## V. Technology Developments

The receiver we used to discover CO had a noise temperature over 4000K (~725hν/K) [10] and an IF bandwidth of 100 MHz, leaving a lot of room for improvement. Room temperature mixers were significantly improved by redesigning the mounting, but Sandy Weinreb [11] soon suggested that Schottky diode mixers could be further improved by cooling them cryogenically. By 1975, Tony Kerr had a cooled Schottky diode receiver operating on the 36-foot telescope with a Single Sideband (SSB) mixer noise temperature of 300K. The best performance of a cooled Schottky mixer receiver was obtained at U. Mass. They achieved an average of 75K DSB over the 80-115 GHz band (150K SSB) [12].

The next big improvement came with the introduction of SIS mixers. Tom Philips and Paul Richards simultaneously described the first lead junction SIS mixers [13],[14]. Despite years of work by IBM, the lead junction technology remained short lived and difficult to use in production receivers. It did serve to start the field and inspire John Tucker to produce the theory of SIS mixers [15].

The final advance in mixers I want to discuss is the change to Niobium. Although the Nb/Al-AlOx/Nb SIS junction process was developed at Bell Labs, they were first used for SIS mixers in radio astronomy at GISS using SIS circuits made at Hypres. The best current receivers in use are the sideband separating receivers for ALMA band 6 [16] and NOEMA band 3 [17] at about 230 GHz. The ALMA receivers have noise temperatures below the specified 80K in most cases over their full RF band and for IF frequencies between 5 and 11 GHz with more than 10 dB image rejection. The NOEMA mixers have noise temperatures "approximately between 40 and 60 K over the whole band of 200 to 268 GHz and the image rejections are almost always better than -10 dB with an average value around -18 dB". The most recent laboratory measurements on SMA receivers have demonstrated a low noise IF bandpass covering 5-18 GHz. Advances in low noise IF amplifiers have been and will be critical here.

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