1

Interstellar Carbon Monoxide

"There are poisons that blind you, and poisons that open your eyes."
August Strindberg, The Ghost Sonata

Celebrating a Toxic Gas

At a resort in the foothills of the Catalina Mountains near Tucson, Arizona, over 225 astronomers from 29 countries gathered on 29 May–5 June 1995 for Symposium No. 170 of the International Astronomical Union, to discuss the topic *CO: Twenty-Five Years of Millimeter-Wave Spectroscopy.*[1] The symposium was organized by the National Radio Astronomy Observatory (NRAO) together with astronomers at the University of Arizona's Steward Observatory. By coincidence, the venue was shared with a convention of the National Rifle Association (NRA). There was confusion over the acronyms on the name tags, the NRA people thinking the astronomers were part of their meeting and vice versa. The gun fans never understood why the astronomers were celebrating the discovery of a gas in outer space, albeit, a gas as lethal as their rifles. Indeed, what was the fascination to astronomers of interstellar carbon monoxide? The explanation begins much earlier.

Interstellar Medium

Astronomers were slow to realize that the space between the stars was not empty. Over the course of the first half of the twentieth century, they came to recognize that a thin haze of gas and microscopic dust particles permeates the space between the stars in the disk of our Milky Way Galaxy. This is the interstellar medium (ISM). The dark voids seen in the constellations of stars were not devoid of stars. Rather, they were vast, intervening clouds of dust,

https://doi.org/10.1017/9781009279727.003 Published online by Cambridge University Press

obscuring our view of the stars that lay behind them. The Atacameños, who had long occupied the area in Chile where ALMA would be built, regarded the dark nebulae of the Southern Sky as their constellations,[2] rather than the stellar constellations familiar to us. Light from stars lying behind the dust clouds is both absorbed and, more importantly, scattered into new directions by the dust. The dust clouds are opaque to visible light much the way that clouds of smoke from fires and dust storms on Earth can obscure our vision. Lists[3] have been made by astronomers of those dust clouds that have reasonably well-defined shapes. The Atacameños saw llamas, birds, shepherds, and foxes, to cite a few examples. It is a wonderful and fitting coincidence that ALMA is now focused on these dark nebulae for a good portion of its observing time.

The first molecule to be discovered in interstellar space was methylidyne (CH) in 1938, soon followed by CH^+ and cyanide (CN). Technically, these molecules are free radicals, highly reactive bits of molecules that exist only fleetingly in the laboratory. In regions of interstellar space, the density of gas and dust is low, lower than the best laboratory vacuum, sufficiently slowing the reactions that destroy the free radicals to make them observable. They were identified by their narrow absorption lines seen in the spectra of bright stars.[4] It took 12 more years before another interstellar free radical was discovered, the hydroxyl radical, OH, by the detection of its spectral line at radio wavelengths.[5] In 1957, Charles Townes discussed the probabilities that other molecules could exist in the ISM.[6] On his arrival in 1967 at the University of California, Berkeley, Townes began a search for molecules in space, starting with ammonia (NH_3). In the fall of 1968, he detected ammonia, and followed that the next year by detecting water (H_2O).[7] Interstellar formaldehyde (H_2CO) was discovered[8] using the NRAO 140 Foot Telescope in 1969. The next year, interstellar carbon monoxide (CO) was discovered in space.

Discovery of Interstellar Carbon Monoxide

The first millimeter wavelength observations at NRAO occurred at its Green Bank, West Virginia, site. Frank Low had moved to Green Bank from Texas Instruments in Dallas, Texas, where he had built a detector of infrared/millimeter radiation using a germanium chip. But the observations made with a small trial dish quickly showed that a drier site with better atmospheric transparency was needed. In 1962, NRAO requested funding from the NSF for a millimeter telescope of diameter 36 ft. Funding was received that same year and Kitt Peak, Arizona, was chosen as the site. It had acceptable atmospheric quality and a well-developed infrastructure. After a difficult period of construction, the telescope came into operation in 1968.[9]

It was intended for continuum observations, that is, recording the strength of millimeter emission in broad chunks of the spectrum. The telescope was also equipped with a filter bank that allowed for spectral line observations.

The team that first detected interstellar CO was composed of Bob Wilson, Keith Jefferts, and Arno Penzias, all of Bell Telephone Laboratories. Their letter[10] requesting observing time on the 36 Foot Telescope stated as the primary goal the detection of CN. Searches for CO and then hydrogen cyanide (HCN) were next in priority. These choices were based on consideration of a number of candidate molecules in the list of Townes and talking with Pat Thaddeus who pointed out the proximity of CN lines to those of CO. Phil Solomon had suggested looking for CO. He thought CO would be an abundant ISM molecule based on its properties.[11] The proposal letter noted that, "*Although CO has a smaller dipole moment than CN, it is also worth looking for owing to the fact that its dissociation energy is above the Lyman continuum making it potentially much more abundant than the other gases heretofore detected in which this is not the case.*" The proposal received only "Average" and "Fair" ratings but was scheduled for observing time nonetheless. Once at the telescope, the team first chose to look for CO. They pointed the antenna to the Orion Nebula, a bright nebula that was overhead at the time their observing run began. It turned out to be the strongest CO source in the sky.[12] They detected it within seconds.

Prior to the observations of interstellar molecules that the detection of CO spawned, the 36 Foot Telescope, shown in Figure 1.1, was not in high demand. It was used mainly to measure the brightness of planets and other radio sources at millimeter wavelengths. The discovery of CO dramatically changed that, and it became NRAO's most popular telescope for a considerable period of time. Its capability at millimeter wavelengths meant it was ideal for observations of interstellar CO and other molecules with spectral lines in the millimeter band. The 36 Foot (later 12 Meter) Telescope remained a productive facility until it was closed in July 2000 to direct resources to ALMA.

The detection[13] of interstellar CO, shown in Figure 1.2, was a watershed discovery, leading to new areas of research in astronomy and transforming others. It all had to do with the formation of new stars. Astronomers knew a great deal at the time about how stars evolve to end their lives, but little about stellar birth. It was assumed that stars formed by the action of gravity, pulling together a stellar mass of material from surrounding space. Star formation was thought to occur in regions where the ISM was of high density. But the high density also meant those regions were unobservable in visible light, no matter how large the (optical) telescope might be. Any light emitted by a newly formed star would be scattered by the surrounding dust, rendering it invisible to an optical telescope. Fortunately, the dust in these regions does not scatter the much longer wavelengths observed by radio telescopes. And the CO in these regions turned out to

Figure 1.1 The NRAO 36 Foot Telescope in its fabric-covered astrodome on Kitt Peak, Arizona. Credit: NRAO/AUI/NSF, CC BY 3.0.

produce a remarkably strong radio signal. For the first time, astronomers could measure the physical properties of star-forming regions of space without their view being obscured by the interstellar dust clouds, allowing them to formulate theories of star formation based on observational data. Fifty years later, ALMA would continue to explore the potential of CO for star formation studies, not only in the Milky Way but in distant galaxies in the Universe.

https://doi.org/10.1017/9781009279727.003 Published online by Cambridge University Press

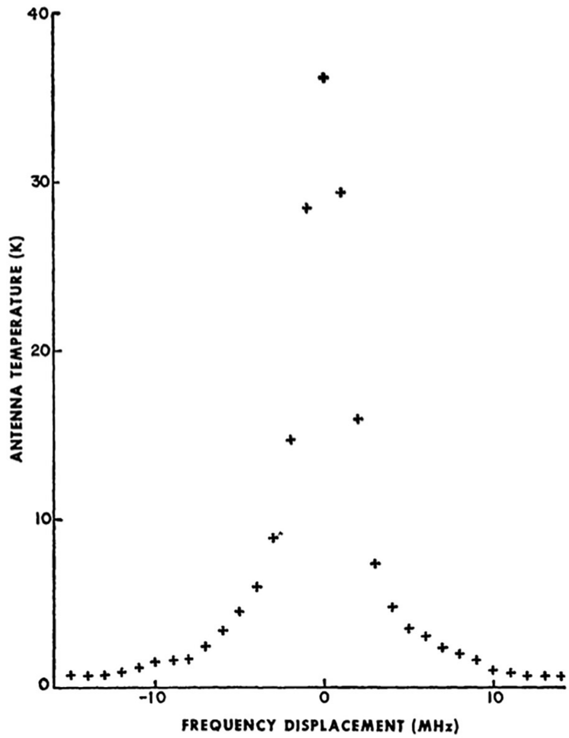

Figure 1.2 The CO signal in the Orion Nebula as first detected. The plot shows the signal strongest at the exact frequency expected for CO in this source, falling dramatically within about ±10 MHz from that frequency. Credit: Wilson, Jefferts, and Penzias (1970); ©AAS, reproduced by permission.

ALMA and the CO Molecule

As an astrochemist, I became involved in the planning of what would become ALMA in the early 1990s, both on the US and European sides. It was clear from the beginning that ALMA would be the "astrochemistry machine" of the future, observing both simple and complex molecules. At that time, CO was already commonly and easily observed in virtually every astronomical source, from planets in our own solar system to star-forming clouds and nearby galaxies, with the high-redshift universe just being opened up in CO.

Although CO is a simple diatomic molecule, its formation in space is very different from that in a laboratory on Earth. The actual chemistry of interstellar CO was elucidated in the 1970s–1980s thanks to close collaboration between astronomers and chemical physicists. The molecule

https://doi.org/10.1017/9781009279727.003 Published online by Cambridge University Press

is formed through a series of ion–molecule reactions starting with C^+ and OH, but once formed it is hard to destroy because of its very strong triple bond: its binding energy of 11 eV is more than double that of other molecules. Only hard UV photons and reactions with He^+ can break CO back into atoms, but even UV destruction is not very effective because of CO self-shielding – a process studied in detail by John Black and myself. Since CO locks up the bulk of the available carbon, the CO abundance is rather constant, so CO is often used to trace the mass of molecular gas because the dominant interstellar molecule, H_2, is invisible in cold gas.

One of the three key science goals in the design of ALMA was to study disks around young stars, specifically "*to image the gas kinematics in solar-mass protoplanetary disks at a distance of 150 pc, …, enabling one to study the physical, chemical and magnetic field structure of the disk and to detect the tidal gaps by planets undergoing formation*". ALMA has certainly more than lived up to this challenge. Not only has it imaged exquisite (sub)structures in the dust continuum indicative of planet formation "in action" but it has also revealed gaps and cavities using CO. Those gas cavities are actually smaller than those of the dust, just as predicted by hydrodynamical models. To draw such conclusions and measure gas surface density profiles, the sensitivity of ALMA is key since one needs to image lines of optically thin CO isotopologs, like ^{13}CO, $C^{18}O$, and in some cases even $^{13}C^{17}O$! Vertical structure also plays a role: in fact, subtle isotope selective processes in the disk surface layers can find their ways into ices and minerals that become the building blocks of planets and that can explain isotope anomalies found in solar system meteorites.

Now that ALMA has been operational for more than a decade, CO continues to surprise us. Our surveys of hundreds of disks have shown surprisingly weak CO emission in the bulk of them, by more than an order of magnitude compared with pre-ALMA models. This is not just due to CO being frozen out onto dust grains in the cold outer part of the disk forming an icy mantle. It seems that under cold high-density conditions, CO is being transformed into other molecules like CO_2, CH_3OH, and hydrocarbons. Moreover, grains grow from interstellar (sub)micron size to pebbles and rocks in disks, which can lock up CO and other ices thereby making them invisible. Thus, even a simple molecule like CO can teach us a lot about the first steps in making planets!

Ewine F. van Dishoeck
Leiden Observatory
The Netherlands

Early Development of Interstellar Molecular Astronomy

The detection of CO, and subsequent detections of many other interstellar molecules, spawned vigorous programs in interstellar molecular spectroscopy at radio telescopes equipped to make millimeter wavelength observations, both in the United States and abroad. By 2022, 267 molecular species were known to exist in outer space.[14] Thirty-six of these have 10 or more atoms (three of these are fullerenes, with 60 or more atoms), complex enough to stimulate speculation about life in space. Many of these molecules were detected with the NRAO 36 Foot Telescope which became the 12 Meter Telescope after a replacement of the reflecting surface in 1983. In Appendix B, we give brief descriptions of the pioneering single-dish millimeter facilities that were in operation in the 1970s, whose success led to the proposal by NRAO to build a 25 m diameter telescope. We also present the subsequent telescopes that were built until recently.

The community of radio astronomers in the United States working at millimeter wavelengths had always felt that they owned the field. After all, they had discovered virtually all the interstellar molecules known prior to 1980, and their pioneering facilities had produced a wealth of information on molecular line sources, the distribution of molecular gas in the Galaxy, and star formation in giant molecular clouds. But the advent abroad of the Institut Radio Astronomie Millimétrique (IRAM) 30 Meter Telescope and the Nobeyama Radio Observatory (NRO) 45 Meter Telescope threatened their leadership in the field. Furthermore, the pioneering facilities had reached their limit for many of the scientific questions being asked. For these reasons, it was agreed that the United States needed a large millimeter telescope. Beginning in 1974, NRAO began studying possible replacements for the 36 Foot Telescope. By July 1977, a conceptual design was complete. The telescope would have a diameter of 25 m, be contained in a protective astrodome with a door that could be opened to the sky, and be located on Maunakea, on the Big Island of Hawaii. A formal proposal was submitted to the NSF for funding.

The proposal received outstanding reviews at the NSF and funding seemed likely. So likely, in fact, that the Decadal Review of Astronomy and Astrophysics for the 1980s (the Field Report) considered it to be a project underway and not needing endorsement. But as it turned out, the future of US millimeter wavelength astronomy would need to lie in some other new facility. That is the subject of the next chapter.

Notes

1 The symposium proceedings were edited by Latter et al. (1997).

2 Technically, the Atacameño “constellations” are *asterisms*, as they are not part of the official 89 constellations recognized by the International Astronomical Union.

https://doi.org/10.1017/9781009279727.003 Published online by Cambridge University Press

3 The dark nebulae targeted by observers for CO observations, for example, L134, L1551, B2, etc., came from the lists of Bok and Reilly (1947) and Lynds (1962).

4 Gerhard Herzberg (1988) summarized the discovery of the first interstellar molecular lines in historical remarks submitted to the *Journal of the Royal Astronomical Society of Canada*. Herzberg received the 1971 Nobel Prize in Chemistry for his contributions to our understanding of the quantum structure of molecules.

5 Sander ("Sandy") Weinreb built a new type of spectrometer for analyzing radio signals, an auto-correlator, as his MIT dissertation project. Using the autocorrelator, he discovered interstellar OH (Weinreb et al., 1963). His invention became the standard spectrometer at many radio telescopes. For many years, Weinreb was the lead electronics engineer at NRAO, making many state-of-the-art contributions to radio astronomy technology.

6 Charles Townes (1957) gave a talk at an IAU symposium in which he presented a list of molecules that he thought were likely to exist in the ISM.

7 Townes (2006) reports the history of the discovery of interstellar water and ammonia.

8 Formaldehyde was the first interstellar molecule to be discovered with an NRAO telescope (Snyder, 1969). It was seen in absorption against numerous sources of continuum radiation. That is, the radiation from a distant source would be absorbed by the formaldehyde, creating spectral lines. Later observers realized that H_2CO lines could be seen against the cosmic background radiation. Many other discoveries of ISM molecules at NRAO would follow, largely with the 36 Foot Telescope.

9 For a history of the 36 Foot/12 Meter Telescope, see Gordon (2005).

10 The letter from A. Penzias to William E. Howard, 27 February 1969, and the reply from D. Heeschen to A. Penzias, 18 March 1969 can be found at NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 4. https://science.nrao.edu/about/publications/alma

11 Solomon and Wickramasinghe (1969) had shown that in regions with a density larger than 100 atoms per cm^3, the gas, overwhelmingly made up of hydrogen atoms (interstellar H had been discovered in 1951 by Ewen and Purcell), would become molecular hydrogen (H_2). After hydrogen, carbon, nitrogen, and oxygen are the most abundant elements in the Universe. The strong bond between C and O in CO meant that once formed it was not easily broken apart and was, potentially, an abundant molecule in the ISM. In fact, we now know it is the most abundant interstellar molecule after H_2.

12 Wilson has published two accounts of the discovery of CO (Wilson, 2008, 2015); the 2008 account is longer.

13 The spectrum is taken from the discovery paper (Wilson, Jefferts, and Penzias, 1970).

14 For a complete list as of 2021, see McGuire (2022).

https://doi.org/10.1017/9781009279727.003 Published online by Cambridge University Press