Perspective from a Younger Generation –
The Astro-Spectroscopy of Gisbert Winnewisser

1 Beginnings – When Molecular Radio Astronomy was still Radio Astronomy

1.1 Introduction

The late 1960s and early 70s were an era of great excitement in all branches of radio astronomy. In spectral line research, 12 years after the detection of the first line, the 21 cm HI hyperfine structure (hfs) transition (Ewen & Purcell 1951), finally the first molecule was found, the hydroxyl (OH) radical (Weinreb et al. 1963).

The OH $\Lambda$-doublet transitions, as well as many other lines at m-, cm- and(!) mm-wavelengths from a variety of molecules, had been identified as possible astronomical targets in a visionary article by Charles Townes (1957).

Shortly after the detection of OH, Hoglund & Mezger (1965) discovered the first radio recombination line, H109α at 5009 MHz. Molecular radio astronomy started in earnest in 1968/9, with the discoveries of ammonia (NH$_3$; Cheung et al. 1968) and water vapor (H$_2$O; Cheung et al. 1969) by a group around Townes$^2$, as well as the first complex organic species, formaldehyde (H$_2$CO; Snyder et al. 1969), breaking loose a real gold rush that has yet to stop. Even today, approximately 2 – 4 “new” interstellar or circumstellar$^3$ molecules are found each year, totaling 126 species (not counting isotopomers)$^4$.

---

$^1$ see also Shklovsky 1952.

$^2$ Both lines were on Townes’ (1957) list!

$^3$ Circumstellar molecules exist in the envelopes of evolved giant stars. Many species are detected there that are also found in interstellar clouds, whereas some others, have so far only been detected in a circumstellar environment.

$^4$ See [http://www.ph1.uni-koeln.de/vorhersagen/molecules/main_molecules.html](http://www.ph1.uni-koeln.de/vorhersagen/molecules/main_molecules.html)
The early history of “molecule-hunting”, interesting us here, is well documented by the review by Snyder (1972; “Molecules in Space”), which gives a very useful introduction to molecular radio astronomy, that is still very much readable today. In the same volume, the review following Snyder’s is by Winnewisser, Winnewisser, & Winnewisser and presents an equally excellent overview of the laboratory side of “Millimetre Wave Spectroscopy”.

Table 1. The First Interstellar “Radio” Molecules

| Name                | Species   | Transition | Frequency (MHz) | Reference               |
|---------------------|-----------|------------|-----------------|-------------------------|
| Hydroxyl            | OH        | $^2{\text{H}_2}J = \frac{3}{2}$ | 1665.4018(2)     | Weinreb et al. 1963     |
| Ammonia             | NH$_3$    | (1, 1)     | 23694.4955(1)   | Cheung et al. 1968      |
| Formaldehyde        | H$_2$CO   | 1$_{11} - 1_{10}$ | 4829.660(1)      | Snyder et al. 1969      |
| Water               | H$_2$O    | 6$_{16} - 5_{23}$ | 22215.08(2)     | Cheung et al. 1969      |
| Methyl alcohol      | CH$_3$OH  | $1^+ - 1^-$ | 834.267(2)      | Ball et al. 1970        |
| Formic acid         | HCOOH     | 1$_{11} - 1_{10}$ | 1638.804(1)     | Zuckerman et al. 1971   |
| Formamide           | NH$_2$CHO | 2$_{11} - 2_{12}$ | 4916.319(3)     | GWi & Churchwell 1975   |
|                     |           | $2_{11} - 2_{12}$ | 4618.55(2)      | Rubin et al. 1971       |
| Cyanocetylene       | HCN      | 1$_{0}$ - 0 | 9095.6537(3)    | Turner 1971             |
|                     | H$^{15}$CN | 1$_{0}$ - 0 | $\sim$ 9060$^d$ | Gardner & GWi 1975a     |
| Acetaldehyde        | CH$_2$CHO | 1$_{10} - 1_{11}$ | 1065.075(5)     | Ball et al. 1971        |
| Methylidine         | CH        | $^2{\text{H}_2}J = \frac{1}{2}$ | 3263.788(10)$^e$ | Rydbeck et al. 1973     |
| Thioformaldehyde    | H$_2$CS   | 2$_{11} - 2_{12}$ | 3139.38(3)      | Sinclair et al. 1973    |
| Methanimine         | CH$_3$NH  | 1$_{10} - 1_{11}$ | 5290.31(4)      | Godfrey et al. 1973     |
| Methylamine         | CH$_3$NH$_2$ | 2$_{02} - 1_{10}$ | 8776.2(1)$^f$   | Fourikis et al. 1974    |
| Vinyl cyanide       | H$_2$CCHCN | 2$_{11} - 2_{12}$ | 1371.8262(1)    | Gardner & GWs 1975b     |
| Methyl formate      | HCOOCH$_3$-A | 1$_{10} - 1_{11}$ | 1610.2445(7)    | Brown et al. 1975       |
|                     | HCOOCH$_3$-E | 1$_{10} - 1_{11}$ | 1610.91(10)     | Churchwell & GWi 1975   |
| Dimethyl ether      | (CH$_3$)$_2$O | 2$_{02} - 1_{11}$ | 9119.668(15)$^g$ | GWi & Gardner 1976     |
| Cyanodiacylene      | HCN$_2$N  | 4$_{-3}$ - 3 | 10650.650(4)    | Avery et al. 1976       |
|                     |           | 2$_{-1}$ - 1  | 5325.328(2)     | Gardner & GWs 1978      |

Only molecules first detected at cm-wavelengths are listed. For early detections in the mm-range, see Snyder 1972. All molecules were first detected in the transitions listed, except for dimethyl ether, which was discovered in its 6$_{06} - 5_{15}$ line at 90938.10(3) MHz by Snyder et al. 1974. No detections for isotopomers are listed, except for HC$_3$N.

Contributions coauthored by GWi are in italics. In most cases these contain essential laboratory spectroscopy work by GWi.

a Apart from the $F = 1 - 1$ line listed, also the 2 – 2 line at 1667.3590(2) MHz was reported in the detection paper. b Line with hfs, intensity-weighted frequency is given. c Line with hfs, average of lowest and highest hfs line frequency is given. d Various lines with differently placed $^{13}$C between 8815 and 9100 MHz. e Apart from the $F = 0 - 1$ line listed, also the $F = 1 - 1$ and $F = 1 - 0$ lines at 3335.475(10) and 3349.185(10) MHz, resp., were reported in the detection paper (frequencies from Rydbeck et al. 1974). f Frequency from Fourikis et al. 1974.
As shown in Table 1, many of the early molecular detections were made at low radio frequencies (and toward Sagittarius B2). A reason for the propensity to find such lines there is given in §1.2.

Almost concurrently with cm-wavelength molecular radio astronomy, shorter wavelength exploration started. Driven by new high-frequency receiver technology and, generally, higher line intensities and a much higher “line density” (i.e. lines per GHz) the “millimeter explosion” started with the discoveries of CO by R. Wilson et al. and HCO\(^+\) (“X-ogen”) by Buhl & Snyder, both in 1970 (the latter published in 1971), and continues through today, having reached the submillimeter range in the 1980s.

Once the millimeter window was opened, (most) people spontaneously lost interest in the cm-range because:

- Most molecules have the bulk or the entirety of their rotational spectrum at (sub)millimeter wavelengths
- Almost all “simple” (di- or triatomic), light molecules have (sub)mm or far-IR (FIR) rotational spectra
- Many of the complex molecules were (for a long time) only found in Sgr B2

Interest remained high in special cm-wavelength lines, including the NH\(_3\) inversion transitions near 24 GHz, a number of prominent maser lines from OH (hfs, 1.7 GHz and higher frequencies), H\(_2\)O (22.2 GHz), CH\(_3\)OH (25, 12.2, and 6.7 GHz), as well as the CH hfs lines (3.3 GHz). All of these, except for CH\(_3\)OH, have all or the bulk of their rotational spectrum at submillimeter and far-infrared wavelengths.

**1.2 Sagittarius B2**

Considering the mm-wavelength data coming in, soon following the radio observations, it became clear that the emission from many low frequency, low-\(J\) lines of complex molecules toward Sgr B2 must be (weakly) inverted. This can be understood (at least for linear or near-linear species) from the fact that “when selection rules for collisional transitions in linear molecules are such that dipole collisions do not dominate, the \(J = 1 - 0\) transitions may have population inversion over a wide range of physical conditions (see, for example Goldsmith 1972)” (quoted from Morris et al. 1976). This is borne out by their statistical equilibrium calculations.

However, direct proof for this assertion came only very recently, from cm-wave interferometry of the CH\(_3\)CHO \(1_{11} - 1_{10}\) (1065 MHz) and HC\(_3\)N \(1 - 0\)

\(^5\) The frequencies are taken from the JPL catalog (Pickett et al. 1998; see [http://spec.jpl.nasa.gov/](http://spec.jpl.nasa.gov/)) or the Cologne Database for Molecular Spectroscopy (Müller et al. 2001; see [http://www.ph1.uni-koeln.de/vorhersagen/molecules/main_molecules.html](http://www.ph1.uni-koeln.de/vorhersagen/molecules/main_molecules.html)). Numbers in parentheses are uncertainties in the last significant digit(s).
4 The Astro-Spectroscopy of Gisbert Winnewisser

(9100 MHz) lines with the Giant Metre Wave Radio Telescope (GMRT; Chengalur & Kanekar 2003) and the Australia Telescope Compact Array (ATCA; Hunt et al. 1999), respectively. The molecular emission is extended over a 2′ × 4′ region and shows a one-to-one correspondence with the continuum emission, proving that it is inverted. For the CH$_3$CHO line a typical optical depth of 0.035 is derived.

Apart from the mentioned lines, Gardner & Winnewisser (1975b) concluded that the vinyl cyanide line listed in Table 1 is inverted, as did Winnewisser & Gardner (1976) for the dimethyl ether line and Sinclair et al. (1973) for the thioformaldehyde line. Broten et al. (1976) inferred the same for the 2.663 GHz $J = 1 − 0$ transition of HC$_5$N.

Once the first complex molecules were found in Sgr B2, this source turned into a Bonanza! The described inversion mechanism together with a relatively strong, extended continuum background “boosted” many otherwise undetectable lines into “observability”. As a consequence, the vast majority of interstellar molecules was and still is found in Sgr B2, many of the most complex ones only there. All of the molecules listed in Table 1 are found in this source.

To put GWi’s Sgr B2 effort into perspective: Several of the lines measured by Gardner and him confirmed “shaky” detections, based on noisy single line observations. The vinyl cyanide work presents the first detection of this molecule in space. The study on different $^{13}$C isotopes of HC$_3$N by Churchwell et al. (1977) indicated chemical fractionation and put a cautionary remark on attempts at determining the carbon isotope ratio in the Galactic center.

1.3 Extended and Compact Organic Molecular Emission in Sgr B2

Using the (low) rotation temperatures and column densities determined for many of the species in Table 1 by Cummins et al. (1986) based on their 2 – 3 mm wavelength line survey it is completely clear that all of the lines in that table must be inverted, which greatly helped their discovery at the time.

Why are these “old” Sgr B2 results still highly relevant today? In large beam observations, such as those of Cummins of al. (angular resolution 90″–180″) one observes very low rotation temperatures for many species. However, interferometer observations by Snyder and collaborators with resolutions < 5″ indicate $T_{rot} \sim 200$ K for the same species in a very compact region, dubbed the “Large Molecule Heimat” (LMH) by Snyder et al. (1994). This source, which is in the immediate vicinity of the Sgr B2(N) continuum source, is the most prolific source of complex molecules known.

Perhaps most interestingly, in recent years arcsecond resolution interferometry with the BIMA Array has resulted in the detection and imaging of increasingly complex organic species, such as CH$_2$CHCN, HCOOCH$_3$, and CH$_3$CH$_2$CN; all Miao et al. 1995, 1997), NH$_2$CHO, HNCO, and HCOOCH$_3$ (Kuan & Snyder 1996), CH$_4$COOH (acetic acid; Mehringer et al. 1997; Remijan et al. 2002), HCOOH (formic acid; Liu et al. 2001), and (CH$_3$)$_2$CO (ace-
The elevated complex molecule abundances in a confined, hot, region, such as the LMH, may be explainable by the evaporation of icy grain mantles, during which molecules that have grown there to complexity by continual hydrogenation over a long time are suddenly released into the gas phase by the ignition of a high-mass embedded star\(^6\). However, such an event cannot possibly explain (for luminosity reasons alone) the unique large-scale distribution of complex molecules in (and maybe around) Sgr B2, which is the most prolific source of organic molecules anywhere and, so far, has only been probed by the low frequency lines described above. If these molecules come off grain mantles, other processes, such as shocks created, e.g., by cloud-cloud collisions must be invoked. There actually is evidence for the latter in Sgr B2 (Mehriniger & Menten 1997; Sato et al. 2000).

1.4 A Giant Organic Cloud around the Galactic Center?

There is actually evidence for a giant repository of organic molecules beyond and including Sgr B2, coextensive with the Central Molecular Zone (CMZ, see e.g. Morris & Serabyn 1996), i.e., stretching from \(l = +1^\circ 6\) to \(-1^\circ 1\) in a \(\sim \pm 0^\circ 3\) wide band around the Galactic center.

The first evidence for extended organic material in the CMZ came from widespread 4.8 GHz H\(_2\)CO absorption (Scoville et al. 1974). Given the ubiquity of formaldehyde in molecular clouds, one might dismiss this “as nothing special”. Methanol (CH\(_3\)OH) on the other hand has usually quite low abundance and is difficult to detect outside hot, dense cloud cores. Nevertheless, Gottlieb et al. (1979) find the emission in the 834 MHz (1\(^+\) – 1\(^-\)) line (see Table \(\text{H}\) in emission and \textit{extended} relative to their 40′(!) beam, concluding it is inverted.

Furthermore, mapping of the HNCO 5\(_{05} – 4_{04}\) transition (made serendipitously simultaneously with a C\(^{18}\)O survey), shows that the emission in this line is extending continuously from \(l = -0^\circ 2\) to \(+1^\circ 7\) (Dahmen et al. 1997). The possible existence of such a huge mass of organic material in our Galactic center is extremely exciting and its extent, chemistry, and excitation should be studied with suitable tracers.

1.5 Randbemerkung: TMC-1

After Sgr B2, GWi and his collaborators turned their attention to complex molecules in cold dark clouds. In the abstract of a paper by Churchwell,\(^6\) A review of complex molecule formation involving grain mantle processes has recently been presented by Ehrenfreund & Charnley (2000).
Winnewisser, & Walmsley (1978) titled fetchingly “Molecular observations of a possible proto-solar nebula in a dark cloud in Taurus”, these authors reported “a small molecular condensation near the south eastern edge of Heiles’ cloud 2” in which they find “strong emission from the $J = 9 – 8$ transition of HC$_5$N and the $J = 1 – 0$ transition of HC$_3$N”, and go on to “refer to this small cloud as the Taurus Molecular Cloud 1, or TMC 1”. It turned out that they started a vogue: As of this writing (2003 October 25) the Astronomical Data System lists a total of 267 abstracts containing TMC 1 in their text.

Churchwell et al. were by no means the first to notice this spectacular source, which lies in the heart of the Taurus molecular cloud complex, and is well known for its high abundance of linear carbon chains, in particular the cyanopolyynes, the longest of which, HC$_{11}$N has only been found there (Bell et al. 1997). Citing them: “Morris et al. (1976) first drew attention to this region by their detection of the $J = 5 – 4$ transition of HC$_3$N; this was followed by the detection of the $J = 4 – 3$ transition of HC$_5$N by MacLeod et al. (1978)[sic] and the $J = 9 – 8$ transition of HC$_7$N by Kroto et al. (1977)”.

A great amount of work on TMC 1 was done by the group at the Herzberg Institute of Astrophysics, GWi’s onetime home, and at the Nobeyama Radio Observatory (NRO), whose 45 m telescope is ideally suited for the 22 – 50 GHz range in which many heavy species at TMC 1’s cold (10 K) temperature have their strongest emission. In a single paper, Kaifu et al. (1987) reported seven(!), strong(!) unidentified lines, which, aided by laboratory work of Saito et al. (1987) and Yamamoto et al. (1987), led to the first identifications of CCS and CCCS.

The NRO’s TMC 1 work culminated with a complete 8800 – 50000 MHz line survey, described by Ohishi & Kaifu (1998), but unfortunately not (yet) published in its entirety, which contains a total of 404 lines from 38 molecules (not counting isotopomers). Eleven of the molecules were newly identified in the course of the survey. It is a great testimony to the laboratory spectroscopists involved that only a single line remains unidentified!

### 2 Light Intermezzo – Interstellar Hydrides

When I was a student, an article by G. Winnewisser, Aliev & Yamada (1982) drew my attention. To quote from its abstract: “The great progress molecular astronomy has made in the past decade has focused attention to one special class of molecules: the hydrides. The presently known spectra of the hydrides are reviewed, both interstellar and laboratory. No interstellar metal hydrides

---

7. http://adsabs.harvard.edu/

8. Mark Morris tells me that the first person to point out TMC 1 to him was Nick Scoville.

9. That paper actually appeared in 1979.
are presently known. A large number of important hydrides exhibit spectra only in the submillimetre and far infrared region. Further technical advances in this area are expected to yield new interstellar detections.”

2.1 Metal-bearing Molecules in the Interstellar Medium

Observations of species containing metals, as well as other refractory species such as SiO, deliver important information on depletion into dust grains. Moreover, when released either from sputtering of the grains or their mantles by violent dynamics, such as protostellar outflows, they can be used as probes of these phenomena (see, e.g. Bachiller 1996).

Today the third sentence quoted above, “No interstellar metal hydrides . . .” is, unfortunately, still true, if we use the strict (chemistry) meaning of “metal” (e.g. Na, K, Mg, Al, Fe, . . .). Four diatomic, non-H-bearing metal compounds (NaCl, KCl, AlCl, and AlF and three triatomic ones (MgNC, MgCN, NaCN, and AlNC) have been detected in the dense envelope of the carbon star IRC+10216 (Cernicharo & Guélin 1987; Guélin et al. 1993; Kawaguchi et al. 1993; Ziurys et al. 1995; Turner et al. 1994; Guélin et al. 1996; Ziurys et al. 2002). MgNC, NaCN, AlF, and NaCl were also found, recently, toward the proto-planetary nebula (PN) CRL 2688 (Highberger et al. 2001, 2003; Ziurys et al. 2002; see Petrie 1999 for a discussion of other candidate species for detection). Still, only one metal-containing molecule, FeO, has been detected in the interstellar medium, toward Sgr B2 (Walmsley et al. 2002).

As to metal hydrides: Radio and (sub)millimeter wavelength searches for interstellar NaH (Plambeck & Erickson 1982) and LiH\textsuperscript{10} have so far been unsuccessful, as was a search for MgH in IRC+10216’s envelope (Avery et al. 1994). Optical wavelength absorption from CaH, AlH, FeH, and MgH has been found in cool stars and the Sun, MgH even in the integrated light of external galaxies (see, e.g., Spinrad & Wood 1965)

2.2 Light Hydrides – Present Status

The history of interstellar hydrides begins with the detection by Dunham (1937) of three optical absorption lines at 3957.7, 4232.6, and 4300.3 Å from diffuse interstellar clouds, which subsequently were found to arise from CH (4300.3 Å; McKellar 1940; suggested by Swings & Rosenfeld 1937) and CH\textsuperscript{+} (the former two; Douglas & Herzberg 1941).

It has been thought for a long time that hydrides might play an important rôle in cooling the highest density regions of interstellar clouds. Hydrides have, firstly, large level spacings, allowing them to emit a relatively large

\textsuperscript{10}The ground state $J = 1 - 0$ transition of LiH is near 444 GHz, an atmospherically very unfavorable frequency. A tentative detection of this line was made in the redshifted ($z = 0.68$) dense absorbing cloud toward the B0218+357 gravitational lens system (Combes & Wiklind 1998).
amount of energy per quantum. Secondly, their large dipole moments require high critical densities for their excitation. Thus, their rotational levels are only excited in high density regions with $n > 10^6$ cm$^{-3}$, making them effective coolants in this regime, where even rare CO isotopes are so optically thick that CO cooling becomes negligible compared to that of (the hydride) H$_2$O.

This regime was excluded in the classical study by Goldsmith and Langer (1978) on “Molecular Cooling and Thermal Balance in Dense Molecular Clouds”, but was re-addressed by Neufeld et al. (1995), who found that for elevated temperatures, $T = 100$ K, H$_2$O cooling dominates and the hydrides’ contribution is comparable to that of all other molecules combined, i.e. $\approx 30\%$ of the former.

Recent detections of hydride rotational transitions were made with the Caltech Submillimeter Observatory (CSO), namely H$_3$O$^+$ [$J_K = 1^-_1 - 2^-_1, 3^-_2 - 2^-_2, 3^-_0 - 2^-_0 / 307, 365, 396$ GHz, Wootten et al. 1991; Phillips et al. 1992], SiH ($^2H_4$, $J = \frac{3}{2} - \frac{1}{2}$, 625, 628 GHz; Schilke et al. 2001)$^{11}$, HCl ($J = 1 - 0 / 626$ GHz; Blake et al. 1985), H$_2$O, H$_2$O$^+$ (110 $-$ 101/557, 548 GHz; Melnick et al. 2000), HDO (the 101 $-$ 000/465 GHz and 111 $-$ 000/894 GHz ground-state transitions; Schulz et al. 1991, Pardo et al. 2001)$^{12}$, and NH$_2$ ($J = \frac{3}{2} - \frac{1}{2}, \frac{1}{2} - \frac{1}{2}, \frac{3}{2} - \frac{1}{2} / 462, 459, 461$ GHz); van Dishoeck et al. 1993). H$_2$D$^+$ (110 $-$ 111/372 GHz), the deuterated isotope of the key H$_3^+$ molecule was discovered with the James-Clerck-Maxwell telescope (Stark et al. 1999)$^{13}$.

Observations with the Long Wavelength Spectrometer aboard the Infrared Space Observatory led to the discoveries of HF ($J = 2 - 1/2.47$ THz; Neufeld et al. 1997), HD ($J = 1 - 0/2.68$ THz and 2 $-$ 1/5.36 THz; Polehampton et al. 2002), plus various H$_2$O, OH, and CH rotational and some H$_3$O$^+$ inversion transitions (many toward Sgr B2; Goicoechea & Cernicharo 2001 and these proceedings).

A preliminary conclusion is that (for the only two sources observed, Orion-KL and Sgr B2) the measured HCl and HF abundances indicate that only a few percent of all chlorine is in these molecules, suggesting significant depletion. If this should hold true for other hydrides as well, their cooling contribution could be much smaller than discussed above. More sensitive observations of more transitions toward more lines of sight are needed. These will be possible with the Herschel Space Observatory$^{14}$ and the Stratospheric Observatory For Infrared Astronomy (SOFIA$^{15}$).

---

11 Tentative detection
12 A number of higher excitation cm and mm-wavelength H$_2$O, H$_2$O$^+$, and HDO transitions have also been found.
13 H$_3^+$ itself was finally detected, after many arduous attempts, in absorption at near-infrared wavelengths by Geballe & Oka (1996), benefitting from a monumental body of laboratory work, mainly gathered by Oka and collaborators (see these proceedings).
14 http://astro.estec.esa.nl/SA-general/Projects/First/first.html
15 http://sofia.arc.nasa.gov/
Under GWi’s direction the KOSMA Spectroscopy Group has produced definitive submillimeter spectroscopy of NH$_2$, C, $^{13}$C, NH, SH, SD, and CF.

### 3 The quest for high spectroscopic precision — “Deutsche Gründlichkeit” gone loose or urgent necessity?

Over the years, the KOSMA lab, with GWi as the driving force, has produced “definitive” spectroscopy (i.e. frequencies to a few times 10 kHz rms up to 1 THz or higher) for a large number of astrophysically important molecules, including the first useful data on many rare isotopomers and various vibrationally excited states.

These are$^{16}$: HC$^+$, HC$^{14+15}$N, $^{12+13}$CO, $^{17+18}$O, $H_2^{12+13}$C$^{16+18}$O, ground-state + vibrationally excited H$^{12+13}$C$_3$, C$_2$H$_2$OCH$_3$, CCS, CCC, ground-state + vibrationally excited HNC, CH$_2$NH, CH$_3$CCH, CCH, $^{32+33}$SO$_2$, S$^{16+17}$O$_2$, C$^{14+15}$N, CH$_2$CCHCN, CCCO, CH$_3$C$_4$H, NH$_2$D (hfs), HC$_5$N, HNCO, and the seven simple species with submillimeter spectra listed above$^{17}$.

The first astronomical detections of C$^{13}$CH and HC$^{15}$N were made by the Cologne group with the KOSMA telescope (Saleck et al. 1992, 1993) and of $^{13}$C$^{17}$O with the Swedish-ESO-Submillimeter Telescope (Bensch et al. 2001).

Among others, the Cologne spectroscopy effort is characterized by, first, comprehensive presentations of the complete spectrum of a given species, in general up to higher (several THz) frequencies than many other listings, and, second, significantly higher accuracy data for many “common” molecules, such as CO and its isotopomers, than available before.

Here we argue, using two examples, that both high frequency accuracy and comprehensiveness are necessary for progress in various different areas.

#### 3.1 Accuracy

Ambipolar diffusion – ion/neutral slip – is an important mechanism in the star-formation process by which magnetic fields initially supporting clouds against collapse slip relative to the neutral gas, leading to the formation of dense cloud cores (see, e.g. Shu et al. 1987). Theory predicts velocity differences < 1 km s$^{-1}$, corresponding to 1 MHz at 300 GHz, between ionic and neutral species (Roberge et al. 1995). In particular, at submillimeter wavelengths present frequency uncertainties for many potentially suitable lines are much too high to draw any reliable conclusions.

---

$^{16}$ For references, see [http://www.ph1.uni-koeln.de/vorhersagen/catalog/catdir.html](http://www.ph1.uni-koeln.de/vorhersagen/catalog/catdir.html)

$^{17}$ Note the tenacity with which cyanoacetylene was pursued!; cf. §1
3.2 Comprehensiveness and Line Confusion

In a recent paper, Kuan et al. (2003) claim to have detected the simplest amino acid, glycine (H$_2$NCH$_2$COOH) in three warm, dense interstellar clouds, including Sgr B2. If true, this would be the conclusion of a long quest (see, e.g., Snyder et al. 1983; Berulis, Winnewisser, Krasnov, & Sorochenko 1985; Combes et al. 1996; Ceccarelli et al. 2000).

Any such “identification” must rely on a large number of lines. Even so (or maybe because of this) the confusion problem is a formidable one. Inspecting any figure presented by Kuan et al. we find comparably many glycine as unidentified (“U”) lines. For a wider view, see the 218 – 263 GHz line survey by Nummelin et al. (1998, 2000), which, for Sgr B2(N), is at or near the confusion limit throughout that band, even at their relatively moderate sensitivity (compared to the interferometric data by Snyder and his collaborators).

In the high density ($n \sim 10^7$ cm$^{-3}$) Sgr B2 “Large Molecule Heimat” (see §1.2) level populations are in Local Thermodynamic Equilibrium characterized by rotation temperatures, $T_{\text{rot}}$, around 200 K (Liu et al. 2001). At this temperature, the lower vibrationally excited states of a large number of complex molecules are populated, giving rise to a plethora of emission lines, probably with comparable intensities to the putative glycine lines. The width of the LMH’s lines, typically $\sim 6–10$ km s$^{-1}$, adds additional complication. Given the gigantic partition functions, many of the lines are weak.

In my opinion, it is completely impossible to conclusively identify very complex molecules in a “line jungle”, such the one found in the Sgr B2 Large Molecule Heimat$^{18}$, if one has not a much better knowledge of, a.o., vibrationally excited lines of many more species than is available today. This means that much more (tedious and little-appreciated) lab work is needed to make progress here: A big job for the Cologne group, which has already measured the spectra (although not necessarily those of the vibrationally excited states) of a number of extant molecules.

Apology

This contribution concerned itself mostly with (some aspects of) GWi’s early astronomical career. Among many others, I didn’t discuss such interesting and important topics as

- NH$_3$ hfs anomalies (Stutzki et al. 1982, 1984; Stutzki & Winnewisser 1985a,b,c)

$^{18}$ High spatial resolution interferometry as employed by L. Snyder and collaborators helps significantly in situations as complicated as the LMH: Individual molecules or groups of molecules in general have slightly different spatial distributions, so that imaging adds an additional dimension to a confident identification.
his pushing the Cologne Acousto-Optical Spectrometers and receivers to become world-class, frontline instrumentation (see, e.g., Schieder et al. 1989; Klumb et al. 1995; Graf et al. 1998, 2003; see also Gary Melnick's SWAS contribution in these proceedings)

any of all the nice KOSMA/Gornergrat results

any of his non-astronomical spectroscopy; little pre-Cologne spectroscopy.

Acknowledgement: I would like to thank Malcolm Walmsley and Lew Snyder for their encouragement.

References

1. Avery, L. W., Bell, M. B., Cunningham, C. T., Feldman, P. A., Hayward, R. H., McLeod, J. M., Matthews, H. E., Wade, J. D.: ApJ, 426, 737 (1994)
2. Avery, L. W., Broten, N. W., MacLeod, J. M., Oka, T., Kroto, H. W.: ApJ, 205, L173 (1976)
3. Bachiller, R.: ARA&A 34, 111 (1996)
4. Ball, J. A., Gottlieb, C. A., Lilley, A. E., Radford, H. E.: ApJ, 162, L203 (1970)
5. Ball, J. A., Gottlieb, C. A., Lilley, A. E., Radford, H. E.: IAU Circ. No. 2350 (1971)
6. Bell, M. B., Feldman, P. A., Travers, M. J., McCarthy, M. C., Gottlieb, C. A., Thaddeus, P.: ApJ, 483, L61 (1997)
7. Bensch, F., Pak, I., Wouterloot, J. G. A., Klapper, G., Winnewisser, G.: ApJ, 562, L185 (2001)
8. Berulis, I. I., Winnewisser, G., Krasnov, V. V., Soroenko, R. L.: Soviet Astronomy Letters, 11, 251 (1985)
9. Blake, G. A., Keene, J., Phillips, T. G.: ApJ, 295, 501 (1985)
10. Broten, N. W., MacLeod, J. M., Oka, T., Avery, L. W., Brooks, J. W., McGee, R. X., Newton, L. M.: ApJ, 209, L143 (1976)
11. Brown, R. D., Crofts, J. G., Godfrey, P. D., Gardner, F. F., Robinson, B. J., Whiteoak, J. B.: ApJ, 197, L29 (1975)
12. Buhl, D., Snyder, L. E.: Nature, 232, 161 (1971)
13. Ceccarelli, C., Loinard, L., Castets, A., Faure, A., Lefloch, B.: A&A, 362, 1122 (2000)
14. Cernicharo, J., Guélin, M.: A&A, 183, L10 (1987)
15. Chengalur, J. N., Kanekar, N.: A&A, 403, L43 (2003)
16. Cheung, A. C., Rank, D. M., Townes, C. H., Thornton, D. D., Welch, W. J.: Phys. Rev. Letters, 21, 1701 (1968)
17. Cheung, A. C., Rank, D. M., Townes, C. H., Thornton, D. D., Welch, W. J.: Nature, 221, 626 (1969)
18. Churchwell, E., Walmsley, C. M., Winnewisser, G.: A&A, 54, 925 (1977)
19. Churchwell, E., Winnewisser, G.: A&A, 45, 229 (1975)
20. Churchwell, E., Winnewisser, G., Walmsley, C. M.: A&A, 67, 139 (1978)
21. Combes, F., Wiklind, T.: A&A, 334, L51 (1998)
22. Combes, F., Q-Rieu, N., Wlodarczak, G.: A&A, 308, 618 (1996)
23. Cummins, S. E., Thaddeus, P., Link, R. A.: ApJS, 60, 819 (1986)
24. Dahmen, G. et al. 1997, A&AS, 126, 197 (1997)
25. Douglas, A. E., Herzberg, G. L.: ApJ, 94, 381 (1941)
26. Dunham, T.: PASP, 49, 26 (1937)
27. Ehrenfreund, P., Charnley, S. B.: ARA&A, 38, 427 (2000)
28. Ewen, H. I., Purcell, E. M.: Nature, 168, 356 (1951)
29. Fournikis, N., Takagi, K., Morimoto, M.: ApJ, 191, L139 (1974)
30. Gardner, F. F., Winnewisser, G.: ApJ, 195, L127 (1975a)
31. Gardner, F. F., Winnewisser, G.: ApJ, 197, L73 (1975b)
32. Gardner, F. F., Winnewisser, G.: MNRAS, 185, 57P (1978)
33. Geballe, T. R., Oka, T.: Nature, 384, 334 (1996)
34. Godfrey, P. D., Brown, R. D., Robinson, B. J., & Sinclair, M. W.: Ap. Lett., 13, 119 (1973)
35. Goicoechea, J. R., Cernicharo, J.: ApJ, 554, L213 (2001)
36. Goldsmith, P. F.: ApJ, 176, 597 (1972)
37. Goldsmith, P. F., Langer, W. D.: ApJ, 222, 881 (1978)
38. Gottlieb, C. A., Ball, J. A., Gottlieb, E. W., Dickinson, D. F.: ApJ, 227, 422 (1979)
39. Graf, U. U., Haas, S., Honingh, C. E., Jacobs, K., Schieder, R., Stutzki, J.: Proc. SPIE, 3557, 159 (1998)
40. Graf, U. U. et al.: Proc. SPIE, 4855, 322 (2003)
41. Guélin, M., Lucas, R., Cernicharo, J.: A&A, 280, L19 (1993)
42. Highberger, J. L., Savage, C., Bieging, J. H., Ziurys, L. M.: ApJ, 562, 790 (2001)
43. Highberger, J. L., Thomson, K. J., Young, P. A., Arnett, D., Ziurys, L. M.: ApJ, 593, 393 (2003)
44. Hoglund, B., Mezger, P. G.: Science, 150, 339 (1965)
45. Hollis, J. M., Lovas, F. J., Jewell, P. R.: ApJ, 540, L107 (2000)
46. Hollis, J. M., Vogel, S. N., Snyder, L. E., Jewell, P. R., Lovas, F. J.: ApJ, 554, L81 (2001)
47. Hollis, J. M., Lovas, F. J., Jewell, P. R., Coudert, L. H.: ApJ, 571, L59 (2002)
48. Hunt, M. R., Whiteoak, J. B., Cragg, D. M., White, G. L., Jones, P. A.: MNRAS, 302, 1 (1999)
49. Kaifu, N., Suzuki, H., Ohishi, M., Miyaji, T., Ishikawa, S., Kasuga, T., Morimoto, M., Saito, S.: ApJ, 317, L111 (1987)
50. Kawaguchi, K., Kagi, E., Hirano, T., Takano, S., Saito, S.: ApJ, 406, L39 (1993)
51. Klumb, M., Frerick, J., Horn, J., Schieder, R., Winnewisser, G. F.: Proc. SPIE, 2583, 420 (1995)
52. Kuan, Y., Snyder, L. E.: ApJ, 470, 981 (1996)
53. Kuan, Y., Charnley, S. B., Huang, H., Tseng, W., Kisiel, Z.: ApJ, 593, 848 (2003)
54. Liu, S., Mehringer, D. M., Snyder, L. E.: ApJ, 552, 654 (2001)
55. MacLeod, J. M., Avery, L. W., Broten, N. W.: ApJ., 233, 584 (1979)
56. McKellar, A.: PASP, 52, 187 (1940)
57. Mehringer, D. M., Menten, K. M.: ApJ, 474, 346 (1997)
58. Mehringer, D. M., Snyder, L. E., Miao, Y., Lovas, F. J.: ApJ, 480, L71 (1997)
59. Melnick, G. J. et al.: ApJ, 539, L87 (2000)
60. Miao, Y., Mehringer, D. M., Kuan, Y., Snyder, L. E.: ApJ, 445, L59 (1995)
61. Miao, Y., Snyder, L. E.: ApJ, 480, L67 (1997)
62. Morris, M., Serabyn, E.: ARA&A, 34, 645 (1996)
63. Morris, M., Turner, B. E., Palmer, P., Zuckerman, B.: ApJ, 205, 82 (1976)
64. Müller, H. S. P., Thorwirth, S., Roth, D. A., Winnewisser, G.: 2001, A&A, 370, L49 (2001)
65. Neufeld, D. A., Lepp, S., Melnick, G. J.: ApJS, 100, 132 (1995)
66. Neufeld, D. A., Zmuidzinas, J., Schilke, P., Phillips, T. G.: ApJ, 488, L141 (1997)
67. Nummelin, A., Bergman, P., Hjalmarson, Å., Friberg, P., Irvine, W. M., Millar, T. J., Ohishi, M., Saito, S.: ApJS, 117, 427 (1998)
68. Nummelin, A., Bergman, P., Hjalmarson, Å., Friberg, P., Irvine, W. M., Millar, T. J., Ohishi, M., Saito, S.: ApJS, 128, 213 (2000)
69. Ohishi, M. & Kaifu, N.: Faraday Discussions No. 109 (1998)
70. Palmer, P., Gottlieb, C. A., Rickard, L. J., Zuckerman, B.: BAAS, 3, 499 (1971)
71. Parde, J. R., Cernicharo, J., Herpin, F., Kawamura, J., Kooi, J., Phillips, T. G.: ApJ, 562, 799 (2001)
72. Petrie, S.: MNRAS, 302, 482 (1999)
73. Phillips, T. G., van Dishoeck, E. F., Keene, J.: ApJ, 399, 533 (1992)
74. Pickett, H. M., Poynter, R. L., Cohen, E. A., Delitsky, M. L., Pearson, J. C., Müller, H. S. P.: J. Quant. Spectrosc. & Rad. Transfer, 60, 883 (1998).
75. Plambeck, R. L., Erickson, N. R.: ApJ, 262, 606 (1982)
76. Polehampton, E. T., Baluteau, J.-P., Ceccarelli, C., Swinyard, B. M., Caux, E.: A&A, 388, L44 (2002)
77. Remijan, A., Snyder, L. E., Liu, S.-Y., Mehringer, D., Kuan, Y.-J.: ApJ, 576, 264 (2002)
78. Roberge, W. G., Hanany, S., Messinger, D. W.: ApJ, 453, 238 (1995)
79. Rubin, R. H., Swenson, G. W., Benson, R. C., Tigelaar, H. L., Flygare, W. H.: ApJ, 169, L39 (1971)
80. Rydbeck, O. E. H., Elldér, J., Irvine, W. M.: Nature, 246, 466 (1973)
81. Rydbeck, O. E. H., Elldér, J., Irvine, W. M., Sume, A., Hjalmarson, Å.: A&A, 34, 479 (1974)
82. Saito, S., Kawaguchi, K., Yamamoto, S., Ohishi, M., Suzuki, H., Kaifu, N.: ApJL, 317, L115 (1987)
83. Saleck, A. H., Eigler, K., Simon, R., Vowinkel, B., Winnewisser, G.: Astronomische Gesellschaft Abstract Series, 7, 83 (1992)
84. Saleck, A. H., Simon, R., Schneider, N., Winnewisser, G.: ApJ, 414, L133 (1993)
85. Sato, F., Hasegawa, T., Whiteoak, J. B., Miyawaki, R.: ApJ, 535, 857 (2000)
86. Schieder, R., Tolls, V., Winnewisser, G.: Experimental Astronomy, 1, 101 (1989)
87. Schilke, P., Benford, D. J., Hunter, T. R., Lis, D. C., Phillips, T. G.: ApJS, 132, 281 (2001)
88. Schulz, A., Güsten, R., Walmsley, C. M., Serabyn, E. 1991, A&A, 246, L55 (1991)
89. Scoville, N. Z., Solomon, P. M., Jefferts, K. B.: 1974, ApJ, 187, L63 (1974)
90. Skhlovsky, I. S.: Astr. Zhur., 29, 144 (1952)
91. Shu, F. H., Adams, F. C., Lizano, S.: 1987, ARA&A, 25, 23 (1987)
92. Sinclair, M. W., Fourikis, N., Ribes, J. C., Robinson, B. J., Brown, R. D., & Godfrey, P. D.: Australian J. Phys., 26, 85 (1973)
93. Snyder, L. E.: *Molecules in Space*. In: *MTP International Review of Science* vol 3, Spectroscopy, ed by D. A. Ramsay (Butterworths, London 1972) pp 193–240
94. Snyder, L. E., Buhl, D., Zuckerman, B., Palmer, P.: Phys. Rev. Lett., 22, 679 (1969)
95. Snyder, L. E., Buhl, D., Schwartz, P. R., Clark, F. O., Johnson, D. R., Lovas, F. J., Giguerre, P. T.: ApJ, 191, L79 (1974)
96. Snyder, L. E., Hollis, J. M., Brown, L. W., Buhl, D., Suenram, R. D., Lovas, F. J.: ApJ, 268, 123 (1983)
97. Snyder, L. E., Kuan, Y.-J., Miao, Y.: LNP Vol. 439: The Structure and Content of Molecular Clouds, 187 (1994)
98. Snyder, L. E., Lovas, F. J., Mehringer, D. M., Miao, N. Y., Kuan, Y., Hollis, J. M., Jewell, P. R.: ApJ, 578, 245 (2002)
99. Spinrad, H., Wood, D. B. 1965: ApJ, 141, 109 (1965)
100. Stark, R., van der Tak, F. F. S., van Dishoeck, E. F.: ApJ, 521, L67 245 (1999)
101. Stutzki, J., Ungerechts, H., Winnewisser, G.: A&A, 111, 201 (1982)
102. Stutzki, J., Olberg, M., Winnewisser, G., Jackson, J. M., Barrett, A. H.: A&A, 139, 258 (1984)
103. Stutzki, J., Winnewisser, G.: A&A, 144, 1 (1985a)
104. Stutzki, J., Winnewisser, G.: A&A, 144, 13 (1985b)
105. Stutzki, J., Winnewisser, G.: A&A, 148, 254 (1985c)
106. Swings, P., Rosenfeld, L.: ApJ, 86, 483 (1937)
107. Townes, C. H.: Microwave and radio-frequency resonance lines of interest to radio astronomy. In: *IAU Symp.* 4: Radio astronomy, ed. H. C. van de Hulst (Cambridge University Press 1957) pp 92–103
108. Turner, B. E.: ApJ, 163, L35 (1971)
109. Turner, B. E., Apponi, A. J.: ApJ, 561, L207 (2001)
110. Turner, B. E., Steimle, T. C., Meerts, L.: ApJ, 426, L97 (1994)
111. van Dishoeck, E. F., Jansen, D. J., Schilke, P., Phillips, T. G.: ApJ, 416, L83 (1993)
112. Walmsley, C. M., Bachiller, R., Forêts, G. P. d., Schilke, P.: ApJ, 566, L109 (2002)
113. Weinreb, S., Barrett, A. H., Meeks, M. L.: Nature, 200, 829 (1963)
114. Wilson, R. W., Jefferts, K. B., Penzias, A. A.: ApJ, 161, L43 (1970)
115. Winnewisser, G., Aliev, M. R., Yamada, K.: *Interstellar Hydrides*. In: *Scientific Importance of Submillimetre Observations* (ESA: SP-189) pp 23 – 28 (1982)
116. Winnewisser, G. Churchwell, E.: ApJ, 200, L33 (1975)
117. Winnewisser, G. Gardner, F. F.: A&A, 48, 159 (1976)
118. Winnewisser, G., Winnewisser, M., Winnewisser, B. P.: *Millimetre wave spectroscopy*. In: *MTP International Review of Science* vol 3, Spectroscopy, ed by D. A. Ramsay (Butterworths, London 1972) pp 241–296
119. Wootten, A., Turner, B. E., Mangum, J. G., Bogey, M., Boulanger, F., Combes, F., Encrenaz, P. J., Gerin, M.: ApJ, 380, L79 (1991)
120. Yamamoto, S., Saito, S., Kawaguchi, K., Kaifu, N., Suzuki, H.: ApJ, 317, L119 (1987)
121. Ziurys, L. M., Apponi, A. J., Guélin, M., Cernicharo, J.: ApJ, 445, L47 (1995)
122. Ziurys, L. M., Savage, C., Hightberger, J. L., Apponi, A. J., Guélin, M., Cernicharo, J.: ApJ, 564, L45 (2002)
123. Zuckerman, B., Ball, J. A., Gottlieb, C. A.: ApJ, 163, L41 (1971)