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Development of the Submillimeter Band

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Abstract. This short article attempts to summarize my contribution to the field of submillimeter spectroscopy in the dense interstellar medium. It is taken mainly from my recollections and as a result some of the dates may be inaccurate. It covers most of the enabling receiver technology from frequencies of about 100 GHz to 2 THz and discusses the development of hot electron bolometers (HEB) and superconducting tunnel junction detectors (SIS). Many new molecular lines and some atomic lines have been revealed. These detectors are in use in the modern major projects such as ALMA and Herschel and will play their part in the many exciting projects of the next decade. Certainly one of the major contributions to the field has been the generation of many students who obtained Ph.D.s (14) and postdocs (25) in my group. The total number of national and international students who have obtained Ph.D.s (75) with use of the Caltech Submillimeter Observatory (CSO) and those who are currently studying using the CSO (44) is even more impressive.

1 Introduction

Microwave spectroscopy of interstellar molecules was a field initiated by Dr. Charles Townes and his group but the fundamental study of molecules in the dense interstellar medium really began with the observation of the $J = 1–0$ ground state rotation line of carbon monoxide (CO) at 115 GHz by Wilson et al. (1970). This was the highest frequency available to radioastronomy at that time and was achieved with the use of the Bell System's Schottky diodes which were available as a result of the earlier unsuccessful attempts to generate a telephone waveguide transmission system for the country. The detection of CO 1–0 indicated that many molecules should be present, in spite of the theoretical prediction that starlight would quickly dissociate them. Very soon thereafter Lew Snyder & Dave Buhl (1971) detected HCN ($T_a \sim 10$ K) and it was suggested to me by Arno Penzias that a detection of DCN might be possible if a receiver could be built for detection of a line of $10^{-5} \times 10\,\mathrm{K} = 10^{-4}\,\mathrm{K}$ which I thought was theoretically possible. In fact, luckily, the DCN line was much stronger, about 1 K, due to chemical fractionation! As a result of these observations several new efforts were developed to try to detect other molecules and indeed higher frequency lines of the CO molecule.

My entry into this field in collaboration with Keith Jefferts (Phillips & Jefferts 1973) was to make use of my low temperature physics background and construct a low temperature receiver. This experimental device was a hot electron bolometer receiver which, in spite of its very limited IF bandwidth, was sufficiently simple and flexible to be used at frequencies from 100 GHz to over 600 GHz — in retrospect an amazing increase in frequency range available to radio astronomy of a factor of about 6. My first use of this receiver was to detect the CO (2–1) line at 230 GHz, which was achieved on the Kitt Peak 11 meter telescope (Phillips et al. 1973). The strength and ubiquity of this transition was indicated by the fact that the first detection was made in the rain through the canvas side of the telescope dome. This surprising detector was a very simple rod of indium antimonide (InSb) which was mounted in the E-field of a full-height waveguide with a directly coupled baseband IF amplifier. The device was matched to the waveguide using an E–H tuner in front and a backshort behind. The waveguide device was mounted in a liquid helium cryostat and possibly represents the first very low temperature mixer receiver for radio astronomy. The way in which this hot electron bolometer worked was to absorb the incoming photons via the electron gas and make use of the temperature variation of the electron resistance due to the fact that the resistance was caused by impurity scattering of the Rutherford type. The scattering is less effective as the electrons speed up resulting in a temperature dependence of the resistance. The original mounting scheme showing a scalar feedhorn and various waveguide tuners is displayed in Figure 1.

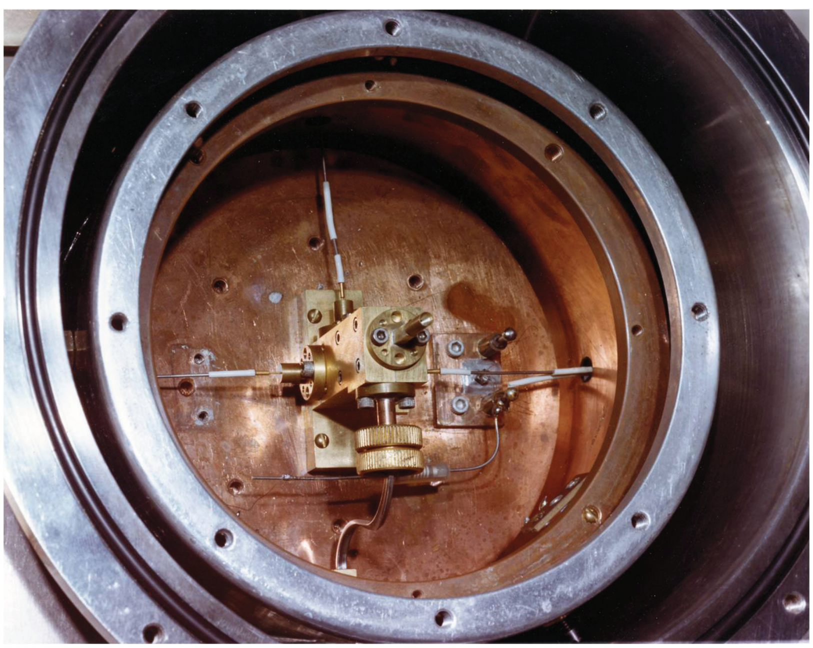

Figure 1. The waveguide mount for the InSb hot electron bolometer. The device is matched to the waveguide by an E–H tuner and a backshort. Any power detector can act as a mixer due to the square-law process.

2 Initial Submillimeter Spectroscopy

The simple InSb detector really opened up the millimeter and submillimeter field of interstellar spectroscopy in spite of the very small IF bandpass (∼1 MHz). If

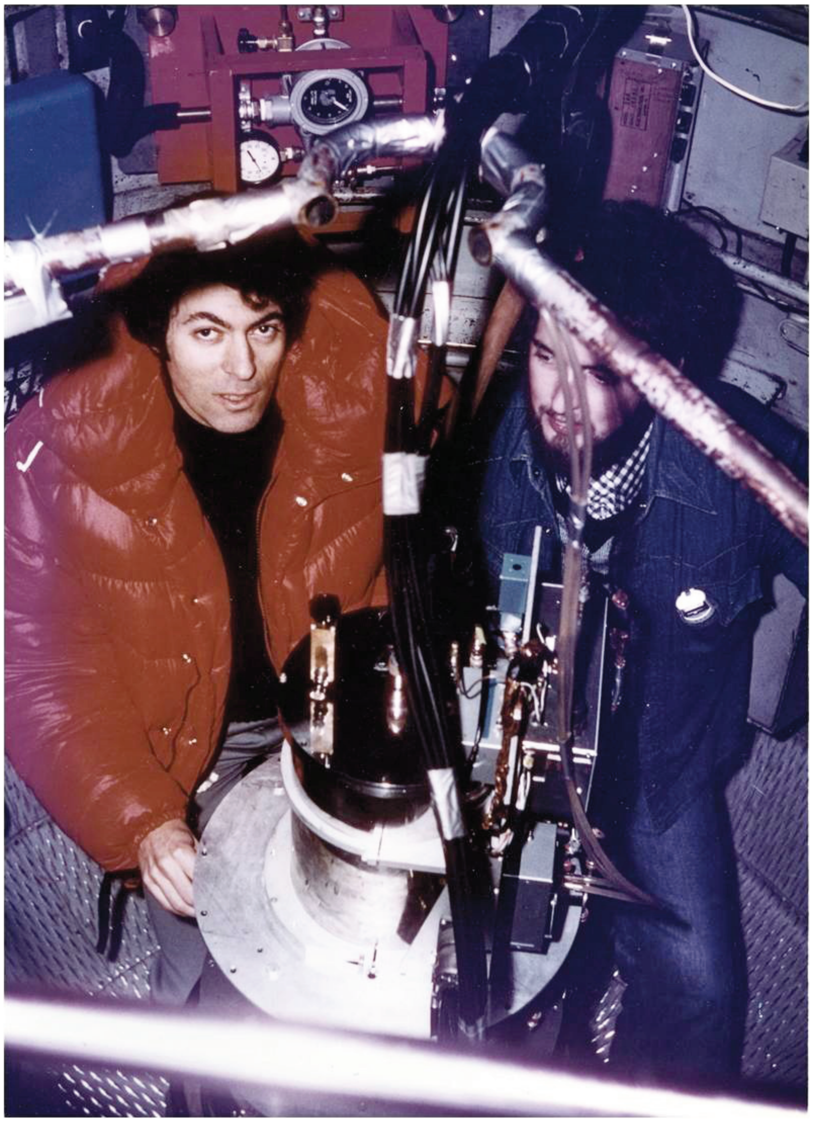

Figure 2. The InSb receiver mounted at the prime focus of the Palomar 200 inch telescope. Tom Phillips and Patrick Huggins are working on it.

the spectrum of the source was needed the local oscillator had to be swept and the single pixel provided the spectrum. If a single channel map were desired the local oscillator was fixed and the telescope swept over the desired area of the sky. The first submillimeter spectroscopy of this kind was the detection of the CO (3–2) line of the Orion Molecular Cloud at the Palomar 200 inch telescope, at a line frequency of 345 GHz. Due to the very high accuracy of the beam of the 200 inch telescope, the separation of the narrow ridge feature of OMC-1 and the broad outflow became very clear. Figure 2 shows a photograph of the InSb receiver mounted at the prime focus of the 200 inch telescope with

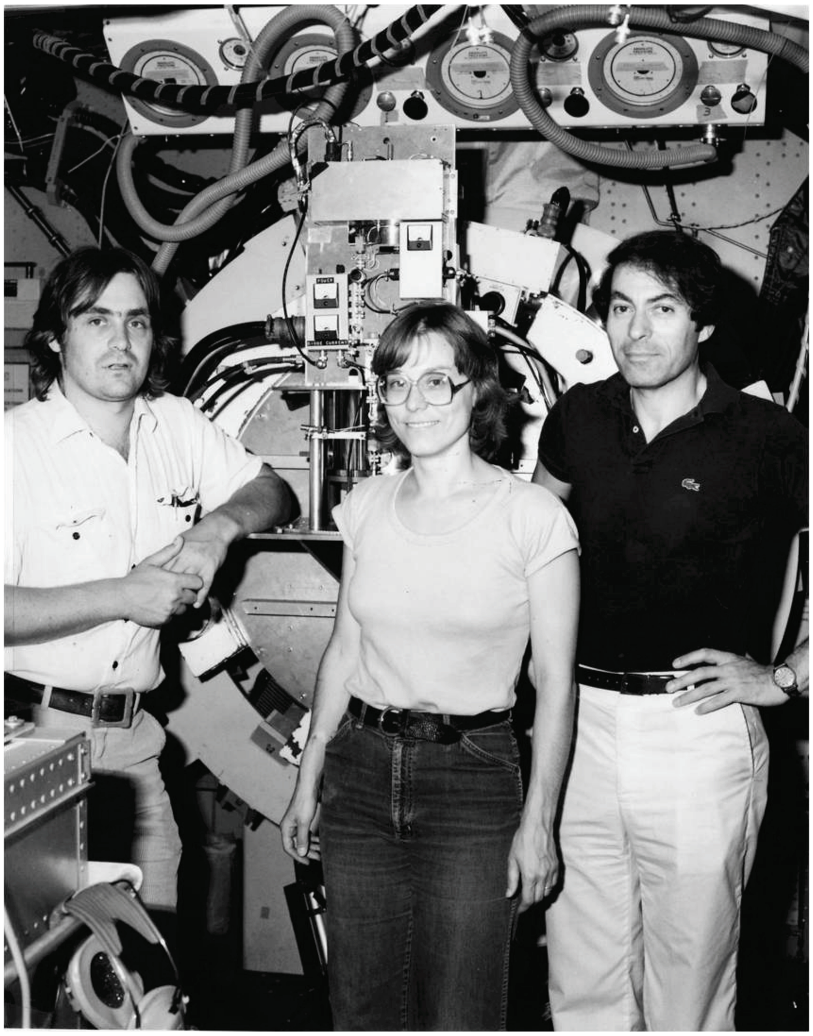

Figure 3. From the left Chas Beichman, Jocelyn Keene, and Tom Phillips at the focus of the 91.5 cm telescope of the Kuiper Airborne Observatory (KAO), operated by NASA.

Phillips and Huggins working on it in the prime focus cage (Phillips et al. 1977). Due to the water and oxygen in the Earth's atmosphere work from the ground becomes very difficult in the submillimeter and as a result some of the effort was switched to operations on the Kuiper Airborne Observatory (KAO). Flying at an altitude of 40,000 feet effectively reduced the attenuation by the atmosphere to a reasonable factor and allowed observations at much higher frequencies. These included the detection of the CO (4–3) line at 460 GHz (Phillips et al. 1980b), the ground state fine-structure line of atomic carbon (C I) at 492 GHz (Phillips et al. 1980a), the fundamental rotational line of ammonia, NH_3 (1–0) at 572 GHz (Keene, Blake, & Phillips 1983), the fundamental rotational line of HCl (1–0) at 626 GHz (Blake, Keene, & Phillips 1985), etc. Figure 3 shows the mounting scheme inside the aircraft fuselage with the InSb receiver at the focus. The telescope was small (91.5 cm) but served the purpose of allowing the discovery of many of the molecular and atomic species present in the dense interstellar medium. Table 1 shows some of the lines and species first detected using the InSb receiver.

Table 1.

Species	Transition	Frequency (GHz)	Reference
CO	$2-1$	230	Phillips et al. (1973)
	$3-2$	345	Phillips et al. (1977)
	$4-3$	460	Phillips et al. (1980b)
C I	$1-0$	492	Phillips et al. (1980a)
NH_3	$1-0$	572	Keene et al. (1983)
HCl	$1-0$	626	Blake et al. (1985)

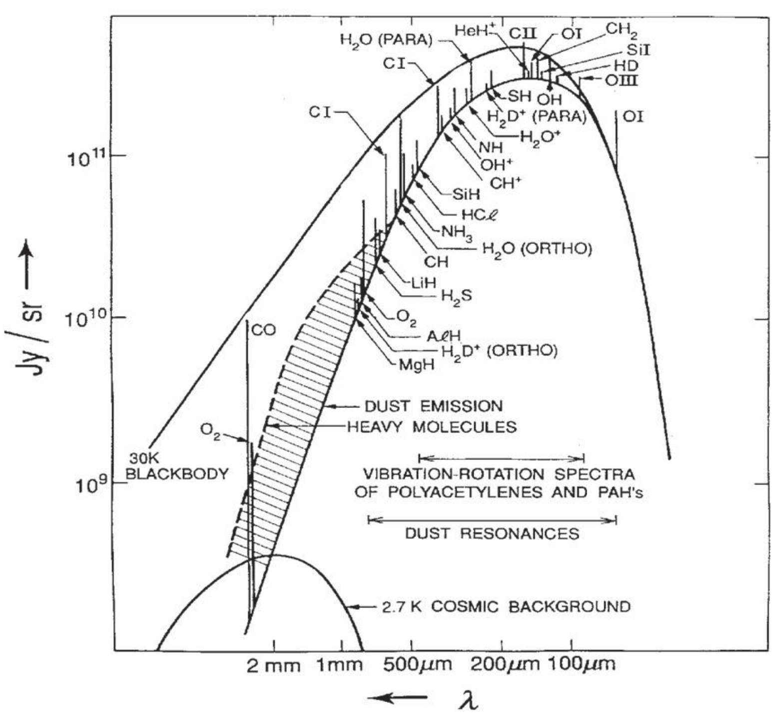

Figure 4. Anticipated spectrum of a 30 K interstellar cloud showing the dust spectrum, the heavy molecule spectrum, and at the short wavelengths, the fast rotating hydride spectra.

Figure 4 is the anticipated spectrum of a 30 K star-forming cloud. The relative strengths of the cosmic background radiation, dust and molecule emission can be seen (Phillips & Keene 1992).

I spent a year (1974–1975) in London and was able to observe during the commissioning time of the Anglo-Australian Telescope (1975) and together with Patrick Huggins and the Australian observers was able to detect CO in the Magellanic clouds for the first time, again using the InSb hot electron bolometer (Huggins et al. 1975). Due to the interest and urging of Professor Martin Ryle, I wrote a proposal for a UK Submillimeter Telescope on a high mountain site which, due in the main part to the extensive efforts of Richard Hills, became the James Clerk Maxwell Telescope (JCMT).

3 SIS Detectors

Although considerable success had been achieved by the hot electron bolometer receiver in opening up a new, complex and interesting field, it was clear that a better receiver was needed as the 1 MHz baseband was unacceptable for a general purpose instrument. The alternative at that time was to attempt to operate the Schottky diode receivers at submillimeter wavelengths. Although this was possible they were rather noisy, so an improved low temperature receiver was required. The low temperature solution to the receiver problem came about, at least in my view, from the intense rivalry between AT&T and IBM in their competition to develop a superconducting computer. Neither company was successful, mainly due to the instability of the lead alloy superconducting tunnel junction electrodes. However they did develop a high frequency switching system using superconducting tunnel junctions which, it seemed to me, (ca. 1975) could be used as fast millimeter or submillimeter wave detectors. Bell Labs supported this and the necessary lithography and excellent collaboration was provided by Ron Miller, Jerry Dolan (sadly now deceased), and Dave Woody.

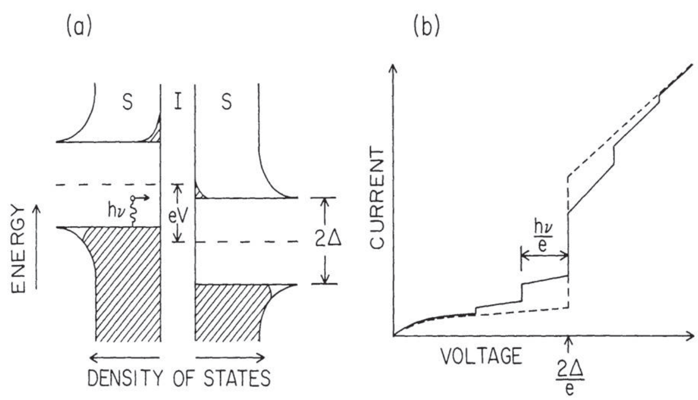

Figure 5. Superconductor-Insulator-Superconductor tunnel junction (SIS). (a) Schematic diagram of the density of states. (b) Current vs. voltage in the absence of RF power (dashed line) and with RF power applied (solid line).

The effect in use is the photon-assisted quasi-particle tunneling discovered by Dayem & Martin (1962) at Bell Labs, but passed over as a device due to the more glamorous Josephson junction discovered soon after, which however, eventually proved too noisy. The physics of this low temperature, quasiparticle, tunneling superconducting device is related to that of the photo-detectors used in the optical and infrared where the band gap of semiconducting materials of about 1 eV is suitable to allow absorption of optical/IR photons. Equivalently the superconducting energy gap of typically 1 or 2 meV is suitable for photo-detection in the millimeter and submillimeter (see Figure 5). The superconducting devices are now known by their structure, "Superconductor-Insulator-Superconductor" (SIS), rather than their physics since the SIS structure supports both quasiparticle and Josephson tunneling. This device, using the lead alloy materials developed by IBM and AT&T, we made to work at 115 GHz in the laboratory in the late 1970s (Dolan, Phillips, & Woody 1979) and mounted on a telescope for the first time also in 1979. We later found out that an independent study was taking place by Paul Richards at 36 GHz (Richards et al. 1979). The lead alloy materials were notoriously unstable both chemically and physically and were eventually replaced by niobium which is acceptably stable. During this time, an excellent theory of the operation of the SIS detector was developed by John Tucker (1979).

The initial Bell Lab detectors were tested on Caltech's prototype millimeter/submillimeter telescope in the Owens Valley. An amazing result was achieved as a result of excellent work by a student (Blake) and postdocs (Sutton et al. 1985; Blake et al. 1986) in which a line-survey spectrum was obtained of the Orion molecular cloud, revealing a very impressive line forest due to heavy molecules in the interstellar medium (see Figure 6). SIS receivers have been chosen for ALMA, probably the outstanding astronomy instrument of the next decade. They also were selected for HIFI on Herschel.

4 The OVRO Interferometer

In 1979 I joined the faculty at Caltech and together with Bob Leighton (sadly deceased) started work on the Caltech Submillimeter Observatory which would consist of the Leighton Telescope with SIS receivers. However, due to a disagreement between Caltech and NSF on the progress made so far with the Owens Valley Interferometer, I was required by Robbie Vogt, the Division Chair at that time, to supervise the construction of the three element interferometer composed of Leighton dishes. This took three years, during which time the NSF provided no funds for the higher accuracy, 4th telescope, but the OVRO interferometer was completed (see Figure 7) and excellent data were emerging by 1984.

5 The Caltech Submillimeter Observatory (CSO)

Despite a lack of funds, Leighton and I had continued to work part time on the submillimeter telescope and had completed the planning for that telescope including the Environmental Impact Statement in Hawaii, the site being on Mauna Kea. By good fortune, NSF funding became available in 1984 and we were able to start work on building our own telescope for the submillimeter. The telescope was completed in 1986 when I became the director. (See Figure 8 where Bob Leighton is hammering in a marker for the telescope foundation and Figure 9 where the telescope and dome are complete).

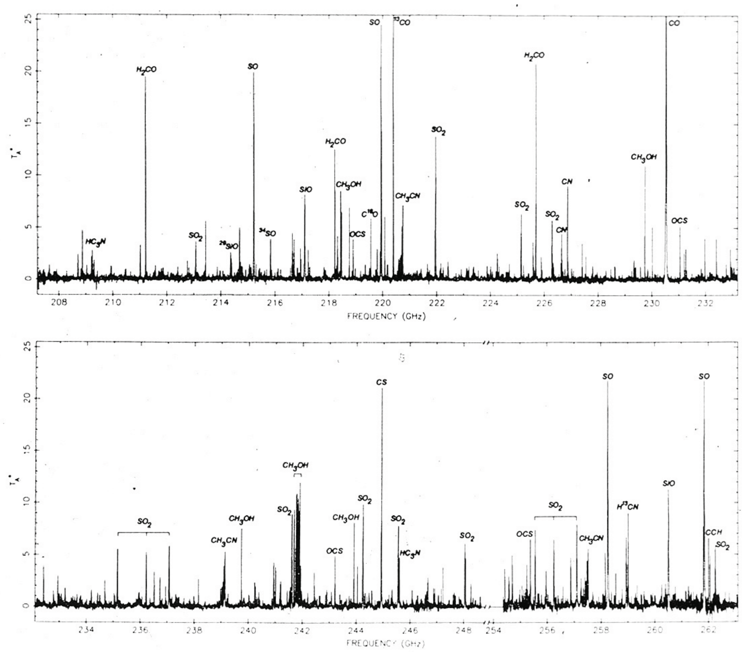

Figure 6. The heavy molecule spectrum as seen in the line survey of Geoff Blake's thesis.

Figure 7. The OVRO Interferometer in 1984.

Figure 8. Bob Leighton marking the site for the CSO.

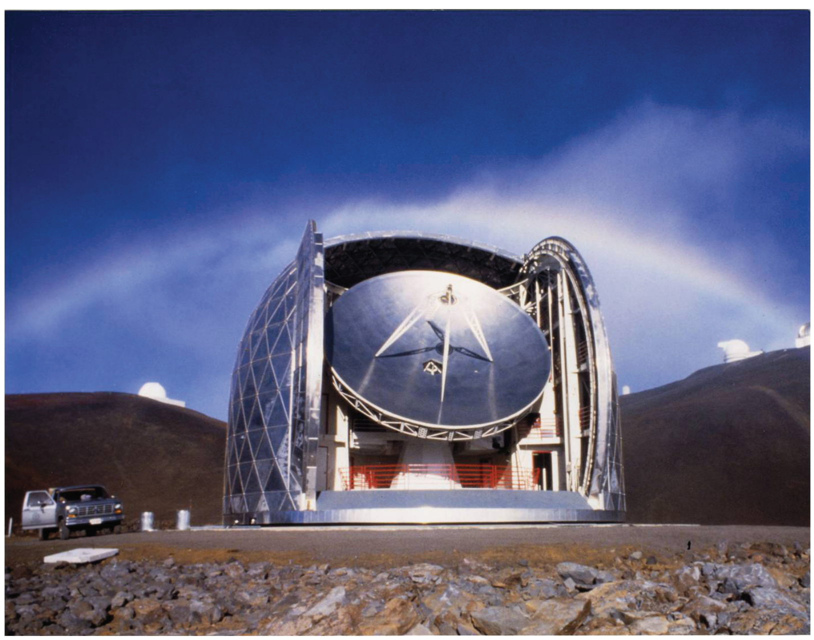

Figure 9. The completed observatory.

Much fascinating work has been carried out at the CSO including the development of high frequency detectors (see Figure 10). This includes several line surveys of interesting objects. An example is Todd Groesbeck's thesis, a component of which is shown in the appendix to this article. Probably the most exciting spectroscopic results have been the observation of deuterated molecules at very much higher abundances than initially expected. See for example the detection of triply deuterated ammonia by Lis et al. (2002). This phenomenon (chemical fractionation) results in deuterium being trapped in cold dense regions possibly requiring a correction to the observed D/H ratios which are measured in warm, low density regions (Phillips & Vastel 2003). Also the same ratio can be measured in comets providing interesting information as to the origin of comets and terrestrial oceans (see Lis et al., this volume).

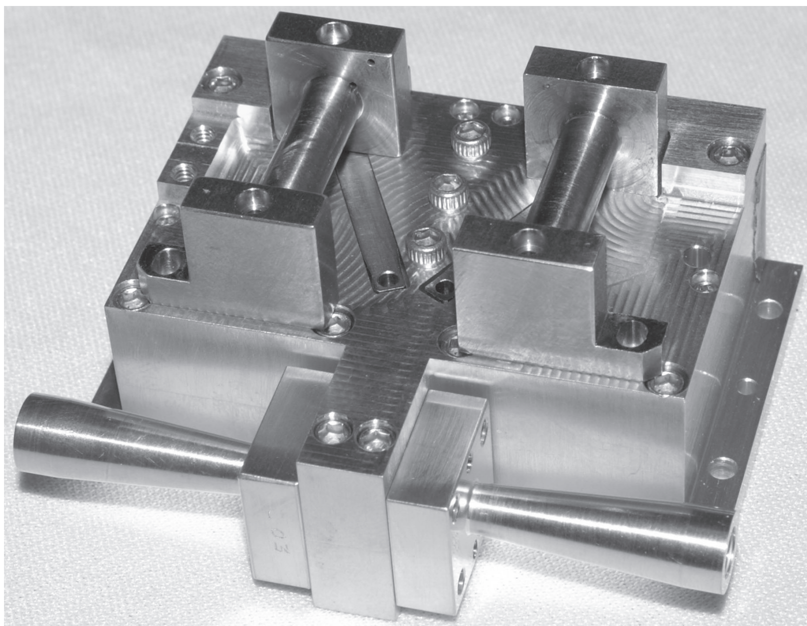

Figure 10. The 345 GHz correlation mixer. The correlation, or continuous comparison mixer covers an RF bandwidth of 280–420 GHz. The correlation receiver is designed for high-z redshift searches, and efficient follow-up on extragalactic sources.

6 From LDR to Herschel

In parallel with the effort to develop submillimeterwave astronomy in the limited available ground-based atmospheric windows I made an effort to produce spectroscopic systems for space application. Although in the US we never achieved a budget for a full space mission, we did start the process which led eventually to HIFI on Herschel (just recently successfully launched in May 2009). In 1979 the decade committee (Field Committee) was persuaded by me and others to support the construction of a large space telescope (Large Deployable Reflector, LDR) for the submillimeter. In fact, both infrared and radio review panels liked the concept and so it was included in the final 1980s report. At about 10 meters in diameter, LDR would have required 3 shuttle loads of panels to be delivered to the space station for assembly by the astronauts. This concept was ruled out by the Challenger accident whereupon NASA instructed us to fit the project into a Delta rocket in the Explorer program. Although there was considerable support for this project in the US, budget considerations forced the Submillimeter Explorer to be behind SOFIA in time, whereas the European project (at that time called FIRST) was budgeted through the Horizon 2000 Program and therefore, although similar to the US project, would happen much earlier. In 1991 three of us, (myself, Charles Townes, and Reinhard Genzel) at a symposium in Liege persuaded the 150 attendees that the two projects, Submillimeter Explorer and FIRST, should be combined. The science community was clearly in favor but it took several years after this meeting before NASA and ESA could agree. NASA was assigned the task of constructing the 3.7 meter diameter fixed aperture telescope but as time progressed, in spite of a successful prototype effort, NASA decided not to continue that task but to hand it over to ESA which had developed a superior silicon carbide technology. Thus NASA's role in the space project now known as Herschel was to provide the elements of the high technology receivers and bolometers for HIFI and SPIRE respectively.

HIFI uses SIS receivers for 10 bands and superconducting versions of the hot electron bolometers for the four highest frequency bands. Having led the US in this direction, I felt somewhat nervous as to whether the project would be completed but it turned out that NASA and ESA did collaborate well. Figure 11 shows the Herschel satellite as it is now at the L2 orbital site. The main result for HIFI (the heterodyne instrument) will be a full understanding of the role of water in the interstellar medium plus some complete line surveys revealing many of the important hydrides and deuterides. It is my expectation that the very tightly bound HF molecule (Neufeld et al. 1997) will prove most useful due to its resistance to dissociation as an example of a species which cannot be observed from the ground. Although it has taken many years to develop the tools for investigation of the submillimeter band, as of today those tools are available or at least in sight. The combination of ALMA, Herschel, CCAT, SOFIA, CARMA, IRAM, and the South Pole telescope will give the submillimeter a role comparable to optical astronomy in importance and may indeed take the lead in investigation of highly distant dusty objects. The submillimeter is here to stay!

7 Students and Postdocs

In the course of this development of the submillimeter field, many students and postdocs have been trained in my group. In fact, their excellent work has resulted in the considerable advances made in submillimeter spectroscopy and in some cases dust continuum studies. In this short article it is impossible to discuss in detail all of their work but student names and thesis topics are listed in Table 2 and postdocs are listed in Table 3. I must say how grateful I am to this excellent group of people without which none of this could have taken place.

In addition to those students and postdocs supervised by me, many students and postdocs either at Caltech with other advisors or at other universities have benefited from the use of the CSO. At this time the extraordinary number of students who have obtained PhDs using the CSO is 75 and those currently studying for their PhDs using the CSO is 44 (see http://www.submm.caltech.edu/cso/cso_phd_students.html).

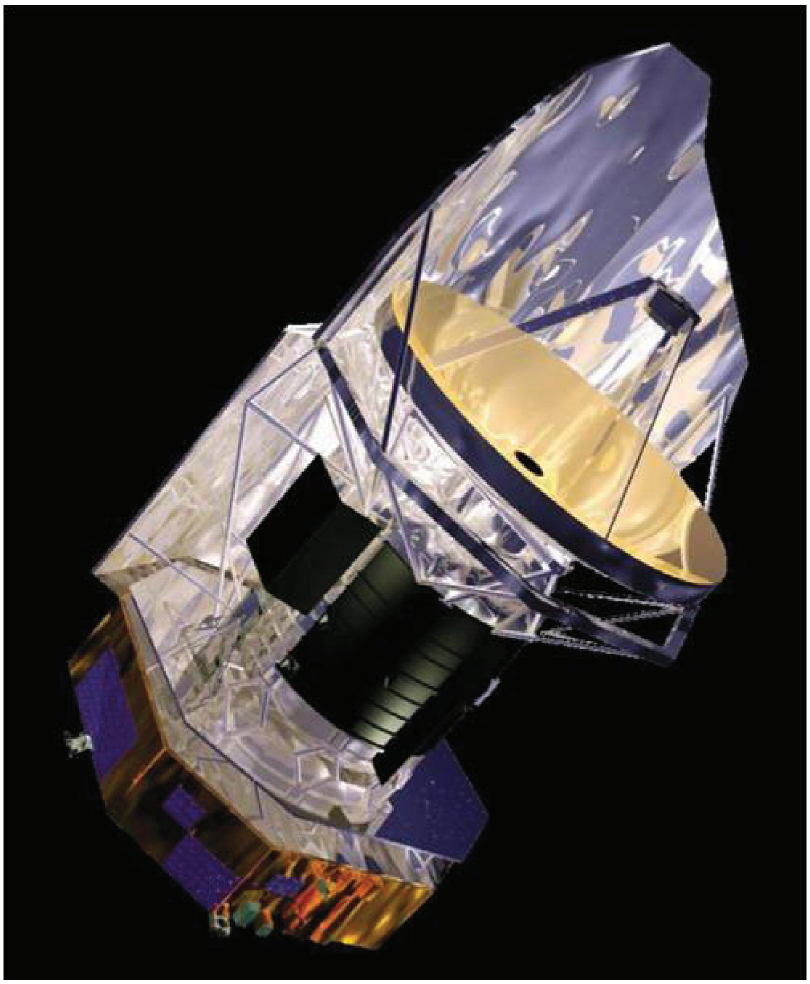

Figure 11. The Herschel satellite launched by the European space agency with the instrument HIFI containing SIS and HEB receivers working up to almost 2 THz.

Table 2. My PhD Students

Student	Year	Thesis Title
Dominic Benford	1999	Broadband submillimeter instrumentation for the detection of distant galaxies
Mei Bin	1997	Low-noise THz niobium SIS mixers
Geoff Blake	1985	On the chemical composition of interstellar molecular clouds: a millimeter and submillimeter spectral line survey of OMC-1
Elliott Brown	1985	Investigation of bulk indium-antimonide as a heterodyne detector for the submillimeter wavelength region
Thomas Büttgenbach	1993	Quasi-optical SIS receivers and astrophysical observations at submillimeter wavelengths
Todd Groesbeck	1995	The contribution of molecular line emission to broadband flux measurements at millimeter and submillimeter wavelengths
Erich Grossman	1988	A far-infrared heterodyne spectrometer for airborne astronomy
Todd Hunter	1996	A submillimeter imaging survey of ultracompact H II regions
Attila Kovacs	2006	SHARC-2 350 μm observations of distant submillimeter-selected galaxies and techniques for the optimal analysis and observing of weak signals
Rob Schoelkopf	1994	Studies of noise in Josephson-effect mixers and their potential for submillimeter heterodyne detection
Jeff Stern	1990	Fabrication and testing of NbN/MgO/NbN tunnel junctions for use as high-frequency heterodyne detectors
Mike Wengler	1987	Heterodyne detection with superconducting tunnel diodes
Min Yang	2006	Submillimeter surveys of galaxy samples
Ken Young (Taco)	1993	Submillimeter and infrared studies of mass lost by asymptotic giant branch stars

Table 3. My Postdocs

Chas Beichman	Raquel Monje
Tom Bell	Frederique Motte
Adwin Boogert	Juan Pardo-Carrion
Colin Borys	Anneila Sargent
Darren Dowell	Peter Schilke
Gerry Dunifer	Gene Serabyn
Tony Gillespie	Ed Sutton
Tom Greve	John Vaillancourt
Patrick Huggins	Charlotte Vastel
Jocelyn Keene	Chris Walker
Darek Lis	Ning Wang
Colin Masson	Dan Watson
Dave Mehringer	

Acknowledgments. I am very grateful to all of my many collaborators over the years, and particularly to my wife, Jocelyn Keene, and also to Gerry Neugebauer and Robbie Vogt for their initial planning efforts in this area and most particularly to Bob Leighton whose beautiful telescopes made the project possible. I am very grateful to the organizers of this conference, Jonas Zmuidzinas, Rena Becerra-Rasti, Tom Bell, Paul Goldsmith, Darek Lis, Nick Scoville, and John Vaillancourt, for the huge amount of work so well done.

References

Blake, G. A., Keene, J., & Phillips, T. G. 1985, ApJ, 295, 501
Blake, G. A., Masson, C. R., Phillips, T. G., & Sutton, E. C. 1986, ApJS, 60, 357
Dayem, A. H., & Martin, R. J. 1962, Phys. Rev. Lett., 8, 246
Dolan, G. J., Phillips, T. G., & Woody, D. P. 1979, Appl. Phys. Lett., 34, 347
Huggins, P. J., Gillespie, A. R., Phillips, T. G., Gardner, F., & Knowles, S. 1975, MNRAS, 173, P69
Keene, J., Blake, G. A., & Phillips, T. G. 1983, ApJ, 271, L27
Lis, D. C., Roueff, E., Gerin, M., Phillips, T. G., Coudert, L. H., van der Tak, F. F. S., & Schilke, P. 2002, ApJ, 571, L55
Neufeld, D. A., Zmuidzinas, J., Schilke, P., & Phillips, T. G. 1997, ApJ, 488, L141
Phillips, T. G., Huggins, P. J., Kuiper, T. B. H., & Miller, R. E. 1980a, ApJ, 238, L103
Phillips, T. G., & Jefferts, K. B. 1973, Rev. Sci. Instrum., 44, 1009
Phillips, T. G., Jefferts, K. B., & Wannier, P. G. 1973, ApJ, 186, L19
Phillips, T. G., & Keene, J. 1992, Proc. IEEE, 80, 1662
Phillips, T. G., Kwan, J., & Huggins, P. J. 1980b, IAU Symp., 87, 21
Phillips, T. G., Neugebauer, G., Werner, M. W., & Huggins, P. J. 1977, ApJ, 217, L161
Phillips, T. G., & Vastel, C. 2003, in SFChem 2002: Chemistry as a Diagnostic of Star Formation, eds. C. L. Curry & M. Fich, 3
Richards, P. L., Shen, T. M., Harris, R. E., & Lloyd, F. L. 1979, Appl. Phys. Lett., 34, 345
Snyder, L. E. & Buhl, D. 1971, ApJ, 163, L47
Sutton, E. C., Blake, G. A., Masson, C. R., & Phillips, T. G. 1985, ApJS, 58, 341
Tucker, J. R. 1979, IEEE J. Quantum Electron., 15, 1234
Wilson, R. W., Jefferts, K. B., & Penzias, A. A. 1970, ApJ, 161, L43

Appendix: CSO Spectral Line Survey of Orion South

Extracted and Adapted from the Ph.D. Thesis by Todd D. Groesbeck[1]

Source Description

Located approximately $1\overset{\prime}{.}5$ south of Orion-KL is Orion-S, another molecular condensation within OMC-1, which has also been identified by various authors as a separate emission peak and referred to as the southern peak (Keene, Hildebrand, & Whitcomb 1982), S6 (Batrla et al. 1983), CS3 (Mundy et al. 1986), and FIR 4 (Mezger, Wink, & Zylka 1990). It was first noted as an active star formation region based on observations of NH_3 lines (Ziurys et al. 1981) and $400\,\mu$m continuum maps (Keene et al. 1982). Interferometer maps at 95 GHz reveal a compact ($10'' \times 4''$) emission source (Mundy et al. 1986). Observations of SiO emission suggested the presence of a bipolar outflow associated with this source (Ziurys & Friberg 1987). High velocity wings are also seen in the CO $J =$ 7–6 line (Schmid-Burgk et al. 1989), while observations of the CO $J = 2$–1 transition towards Orion-S have demonstrated the highly collimated and extended nature of the bipolar outflow (Schmid-Burgk et al. 1990). Recent interferometer maps of several molecular lines have shown that the molecular abundances are somewhat depleted in the compact core of Orion-S (McMullin, Mundy, & Blake 1993). Relative to the fractional abundances found towards the components of Orion-KL, the chemistry in Orion-S appears to resemble most closely that of the quiescent gas in the extended ridge. This has been interpreted to suggest that Orion-S is at an earlier stage of chemical and physical evolution than the condensations in the Orion-KL region and that the Orion-S outflow has not yet had a significant impact on the molecular abundances there (McMullin et al. 1993).

Our observations were centered on a nominal source position of $\alpha(1950) = 05^{\mathrm{h}}32^{\mathrm{m}}46\overset{\mathrm{s}}{.}13$, $\delta(1950) = -05°26'01''$ using the same source velocity (VLSR $= 9$ km s^{-1}) as assumed for Orion-KL. The survey data are shown in reduced SSB form in Appendix A in the thesis, with tables listing the lines detected and their intensities. The most striking differences between the spectra of Orion-KL and Orion-S are the reduced number of lines detected, the narrower line widths seen towards Orion-S and the near absence of SO_2 emission towards Orion-S. As discussed below, the integrated line emission and the contribution of the lines to the total flux are therefore greatly reduced relative to the Orion-KL case.

Observed Line Flux

The spectrum of Orion-S obtained from the CSO spectral line survey is presented in Appendix A of the thesis; a compressed version is shown in Figure 12.[2] We summarize here the survey data as it relates to the integrated line flux. A total

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[1] The complete thesis is posted online at http://www.submm.caltech.edu/cso/oris/.

[2] Originally Figure A 2.2 in the thesis.

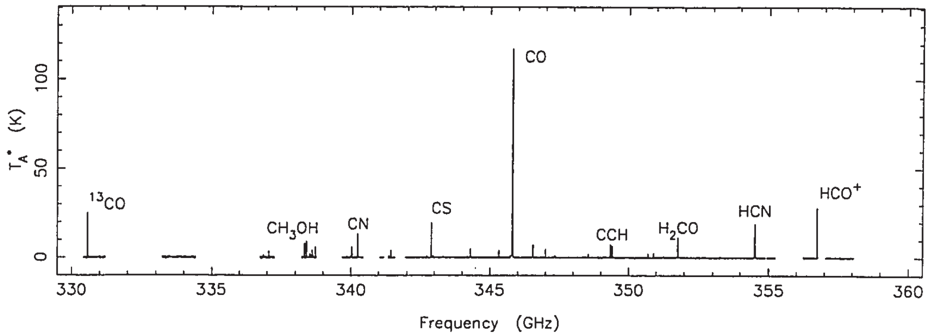

Figure 12. A compressed view of the CSO spectral line survey of Orion-S.

of 43 scans were combined to yield the final survey spectrum, which partially covers the frequency range from 325 to 360 GHz. Time constraints coupled with the weaker emission from this source made it imperative to select particular frequencies for observation, particularly those at which strong emission or particular species were observed towards Orion-KL. Choosing to observe these frequencies had the dual benefits of increasing the likelihood that the majority of the line flux would be included in our observations (for the case where strong emission was also observed towards Orion-S) and of allowing distinguishing characteristics of the two sources to be observed (for the case where strong emission was not detected towards Orion-S). Hence we have particular scans which include frequencies corresponding to the CH_3OH band near 338 GHz and the SO_2 band near 358 GHz, for example. Some 63% of the band between 330 and 360 GHz is included in our final set of combined observations, with the particular scan information given in Appendix A of the thesis. Appendix A also contains tables showing the particular lines detected in the Orion-S survey and giving transition and intensity information. A total of 78 spectral features, identified with 108 molecular transitions, were detected, with only 2 features remaining unidentified. We believe that more sensitive observations would be likely to detect additional lines, including features which would not be identifiable with known transitions. All of the species for which emission was observed in Orion-S were also seen in Orion-KL.

The lines in Orion-S are generally weaker and much narrower than the corresponding lines in Orion-KL, thus yielding a much reduced integrated line flux. For example, while the CO $J = 3$–2 line has a roughly comparable peak temperature (118 K as compared to 144 K), the integrated area is reduced by a factor of 4 ($995\,\mathrm{K\,km\,s^{-1}}$ versus $4178\,\mathrm{K\,km\,s^{-1}}$). Even greater reductions occur in the integrated areas of lines from other molecules which exhibited broad emission in Orion-KL, e.g., HCN, CS, SiO, and SO. The near absence of SO_2 emission in Orion-S results in an integrated line flux from this species which is reduced by two orders of magnitude; since SO_2 emission is responsible for 28% of the integrated line flux in Orion-KL this is of tremendous significance for the total line flux in Orion-S. Table 4[3] shows the contributions of the most significant species to the integrated line flux as seen by our survey. As was the case for Orion-KL, the survey data permit a direct comparison between the detected line flux and the continuum flux as determined from the average baseline offset. In general, the baselines were somewhat easier to determine for these observations because of the reduced line emission. We deduce an uncorrected continuum emission value of 0.8 K, with the same uncertainty as before (15% in addition to the overall calibration uncertainty estimated at 20%). The average integrated line flux over the range of observed frequencies is found to be 0.11 K, so that the integrated line flux represents 12% of the total flux detected by our observations.

Table 4.

SIGNIFICANT FLUX CONTRIBUTIONS BY SPECIES FOR ORION-S

Species [a]	N_{lines}	$\int T_{MB}\, d\nu$ (K MHz)	Relative Contribution (% of Total Line Flux)
CO †	3	1313.2	48.9
CO	1	1148.6	42.8
CH_3OH	27	264.4	9.8
HCO^+ †	2	226.2	8.4
HCN †	3	220.3	8.2
CS †	2	141.9	5.3
CN	10	119.7	4.5
SO †	3	95.0	3.5
H_2CO †	2	91.6	3.4
C_2H	2	88.8	3.3
SO_2	19	44.1	1.6
CH_3OCH_3	24	5.8	0.2
U-lines	2	1.7	0.1

[a] Values for species marked with a † also include the contributions of all transitions detected from isotopomers and vibrationally excited states. For CO, entries are shown both for the main species and for all of the variants together.

This value may be taken to be an upper limit for the line flux contribution that would be detected in a complete survey because the observations are chosen to include the regions of strongest line emission. It is therefore unlikely that a continuous survey, including frequency ranges where no strong lines occur, would have the same average line emission. Instead, the line emission would be likely to be reduced when averaged over a broader range of frequencies, although this depends on the particular frequencies included, of course. By comparison, the continuum emission is relatively insensitive to the particular frequencies observed within the fairly limited range of our survey. We may deduce a lower limit by assuming that no additional line flux would be detected in such a survey, simply

[3] Originally Table 5.3 in the thesis.

scaling the observed average line flux by the relative frequency coverage. For the present survey data, this yields a value of 0.07 K for the line flux averaged over the entire 330–360 GHz window, or 8% of the total flux observed. Considering the upper and lower limits thus found, we may conclude that the molecular emission lines contribute ~10% to the total flux for Orion-S at these wavelengths.

As was noted above, this value is greatly reduced when compared to the line flux for Orion-KL because of the narrower, weaker lines and because of the absence or near absence of various species, most notably SO_2. The comparison of line flux and continuum emission has the advantage of being a direct comparison utilizing the same data, and while the frequency coverage of the survey is incomplete, the rather low value for the line flux contribution results is fairly well constrained.

Extrapolation for Weak Lines

We again estimate the contribution of undetected lines by extrapolating a power-law fit to the line distribution as a function of the integrated intensity. The fit is significantly flatter than our fit to the Orion-KL line distribution, although this may in part reflect a general undercounting of weak lines which might result from the bias of our observations towards strong lines. Extrapolating this flatter distribution would suggest that the observed line flux should be increased by only ~7% to account for undetected lines. Thus our estimate of the line flux contribution would not be significantly changed from the above value of ~10%.

Comparison with Additional Flux Measurements

As part of their single-dish mapping of the OMC-l region, Mezger et al. (1990) have made 1.3 mm observations of Orion-S (FIR 4 in their notation). When their observations are smoothed to 21″ resolution, they obtain a total broadband flux of ~25 Jy towards Orion-S. The 400 μm observations of Keene et al. (1982) give a value of 900 Jy in a 35″ beam. A simple fit to these values yields a spectral index of 3 for the total flux from Orion-S. Additional data is available at 3 mm from interferometer maps by Mundy et al. (1986), where the flux from Orion-S (their CS3) is 0.6 Jy for a $10'' \times 4''$ source size. They estimate that 20%–50% of the dust emission is recovered by the interferometer observations; a total flux of 2 Jy, corresponding to 30% recovery, agrees very well with the simple fit to the 1.3 mm and 400 μm data. From this fit, we obtain an estimated total flux of 83 Jy at 870 μm, which compares well with our total observed flux of 74 Jy (again assuming a small source as for Orion-KL).

As noted before, Mezger et al. estimate a correction for integrated line emission at 1.3 mm of ~40% for the Orion-KL region (their FIR I region). They also estimate a correction of ~30% for the Orion-S region (their FIR 4), noting only that the confusion of line emission with broadband dust emission occurs to a lesser extent there and is not a problem in cooler regions or outside the emission peaks. Given our findings above, the 30% correction for Orion-S appears likely to be an overestimate, although we do not have observational data at 1.3 mm to verify this.

Summary

The integrated line emission from Orion-S is found to be much less than that from Orion-KL, while the continuum emission is reduced by a lesser amount. The overall result is that the contribution of molecular line emission to broadband flux measurements is only $\sim$10% for the 330–360 GHz window, as found by direct comparison of the continuum and line emission detected by our survey. A number of factors contributing to the reduced line emission have been noted, including the nearly absent or greatly reduced emission from particular species (most notably SO_2) and the reduced brightness temperatures and greatly reduced line widths in general, particularly for species which had exhibited emission from the Orion-KL plateau. The line distribution as a function of intensity appears to be less steep than for Orion-KL, so that the estimated correction for undetected weak lines is also reduced and would only produce an increase of $\lesssim$10% in the total line flux. Simulations of the molecular emission compared with a simple model dust spectrum suggest that the contribution of the integrated lines is unlikely to increase at other frequencies.

References

Batrla, W., Wilson, T.L., Bastien, P., & Ruf, K. 1983, A&A, 128, 129
Keene, J., Hildebrand, R. H., & Whitcomb, S. E. 1982, ApJ, 252, L11
Mezger, P.G., Wink, J.E., & Zylka, R. 1990, A&A, 228, 107
McMullin, J. P., Mundy, L. G., & Blake, G. A. 1993, ApJ, 405, 599
Mundy, L.G., Scoville, N.Z., Bååth, L.B., Masson, C.R., & Woody, D.P. 1986, ApJ, 304, L51
Schmid-Burgk, J., Guesten, R., Mauersberger, R., Schulz, A., & Wilson, T. L. 1990, ApJ, 362, L25
Schmid-Burgk, J., et al. 1989, A&A, 215, 150
Ziurys, L.M., & Friberg, P. 1987, ApJ, 314, L49
Ziurys, L.M., Martin, R. N., Pauls, T. A., & Wilson, T. L. 1981, A&A, 104, 288