CALIFORNIA INSTITUTE OF TECHNOLOGY

Division of Physics, Mathematics, and Astronomy

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FINAL TECHNICAL REPORT

for

NASA-Ames Agreement NAG2-744
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Submillimeter Spectroscopy with a 500–1000 GHz SIS Receiver

Contents

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1   Introduction

This is the final technical report for NASA–Ames grant NAG2-744 to Caltech, entitled "Sub-millimeter Spectroscopy with a 500–1000 GHz SIS Receiver", which extended over the period October 1, 1991 through January 31, 1997. The purpose of the grant was to fund the development and construction of a sensitive heterodyne receiver system for the submillimeter band (500–1000 GHz), using our newly–developed sensitive superconducting (SIS) detectors, and to carry out astronomical observations with this system aboard the NASA Kuiper Airborne Observatory (a Lockheed C-141 aircraft carrying a 91 cm telescope). A secondary purpose of the grant was to stimulate the continued development of sensitive submillimeter detectors, in order to prepare for the next–generation airborne observatory, SOFIA, as well as future space missions (such as the ESA/NASA FIRST mission).

The construction of our instrument was started in October 1991, and the first observing flights were taken in September 1992. Table I lists all of the observing flights taken with our instrument before the KAO was decommissioned in October 1995 (in preparation for SOFIA).

TABLE I
Flight Series with the KAO

Year	Month	Flight Dates
1992	September	24, 28, 29
1993	June	18, 21, 23
1994	February	4, 7, 9
1994	June	22, 23, 27, 29
1994	July	24, 25
1995	June	20, 22, 24, 26

2   Observations and Scientific Results

2.1   Hydride Molecules in the Interstellar Medium

An important goal of submillimeter astronomy is the study of hydride molecules, which have their fundamental rotational transitions in the submillimeter band. Table II gives a listing of the transition frequencies for many of the important hydrides. From this table, it is apparent that many of these transitions are not observable from the ground. Observations of these molecules are important for testing our understanding of the chemistry of molecular clouds, since the hydrides are the initial products of the ion-molecule reaction network which is

thought to be responsible for the synthesis of more the more complex molecules commonly observed at radio and millimeter wavelengths. In addition, hydrides may play a crucial role in the energetics of molecular clouds, particularly at the high densities found in star-forming cores, because their large rotational level spacings and large dipole moments make them very effective coolants.

One of the major uncertainties regarding the hydride molecules is their abundance. There are large variations in the predictions of chemical models due to uncertainties in the rates of key reactions. In addition, the importance of processes involving dust grains is poorly understood at best. Depletion out of the gas phase and onto the grains can radically alter the chemical composition of the molecular gas and its capacity to cool itself through rotational emission. Submillimeter observations can probe the abundance of various hydrides in relatively cool, quiescent regions, through absorption-line spectroscopy of the ground-state transitions using embedded hot dust cores as continuum sources.

2.2   Observations of $H_2^{18}O$

Oxygen is the third most abundant element in the interstellar medium and is at least twice as abundant as carbon (Anders & Grevesse 1989). Little is firmly understood about the chemistry of oxygen in interstellar molecular clouds. Oxygen is present in gas-phase species such as CO, O, O_2, and H_2O, and in the solid phase as silicates in the cores of dust grains and also as H_2O and CH_3OH ice mantles on grains.

Gas-phase water is especially interesting because of its potentially important role in the energy balance of molecular clouds, through radiative cooling (or heating) by the far-infrared rotational transitions (Scoville & Kwan 1976; Goldsmith & Langer 1978; Takahashi, Hollenbach, & Silk 1983, 1985; Neufeld & Kaufman 1993). Unfortunately, the opacity of the Earth's atmosphere makes observations of interstellar water difficult. Several transitions have been detected from the ground, including the $6_{16} - 5_{23}$ masing line at 22 GHz (Cheung et al. 1969), the $3_{13} - 2_{20}$ line at 183 GHz (Waters et al. 1980; Cernicharo et al. 1994), the $4_{14} - 3_{21}$ line at 380 GHz (Phillips, Kwan, & Huggins 1980), and submillimeter masers (e.g. Menten, Melnick, & Phillips 1990). In addition, Jacq et al. (1988) and Gensheimer et al. (1996) observed the 203 GHz $3_{11} - 2_{20}$ transition of $H_2^{18}O$. However, all of these transitions involve energy levels $\gtrsim$ 200 K above the ground state, and do not sample the bulk of the molecular gas which has temperatures near $10 - 20$ K.

Chemical models predict $H_2O/H_2 \sim 10^{-6}$ in cool regions, but these estimates vary widely because the abundances of the key species involved in the formation and destruction of H_2O are poorly constrained (Wannier et al. 1991). Water molecules in cool regions radiate mainly in the ground-state transitions at 557 GHz, 1113 GHz, and 1670 GHz. Although the 557 GHz line may have been detected in Orion by a recent balloon experiment (Tauber et al. 1995), future space (e.g. SWAS, ODIN, FIRST) or balloon-borne (e.g. PIROG)

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TABLE II
SELECTED SUBMILLIMETER LINES

Species	Transition	Frequency (GHz)	E_{lower} (K)	Atmospheric (1 mm H_2O)	Transmission (KAO)
C	$^3P \; J = 1 \to 0$	492.16	0.0	30 %	99 %
SH^+	$N = 1 \to 0; \; F = 5/2 \to 3/2$	526.05	0.0	2 %	99 %
CH	$F_1 \to F_2; \; J = 3/2^+ \to 1/2^-$	532.73	0.2	1 %	98 %
$H_2^{18}O$	$1_{10} \to 1_{01}$	547.68	34.2	0 %	81 %
^{13}CO	$5 \to 4$	550.93	52.9	0 %	56 %
$^{15}NH_3$	$1_0 \to 0_0$	572.11	0.0	0 %	94 %
NH_3	$1_0 \to 0_0$	572.50	0.0	0 %	94 %
CO	$5 \to 4$	576.27	55.3	0 %	80 %
SiH	$F_1 \; J = 3/2^- \to 1/2^+$	624.92	0.0	10 %	99 %
$H^{35}Cl$	$1 \to 0$	625.92	0.0	15 %	99 %
SiH	$F_1 \; J = 3/2^+ \to 1/2^-$	627.69	0.0	21 %	98 %
CO	$6 \to 5$	691.47	83.0	30 %	97 %
$H_2^{18}O$	$2_{11} \to 2_{02}$	745.32	100.6	0 %	82 %
CO	$7 \to 6$	806.65	116.2	29 %	97 %
C	$^3P \; J = 2 \to 1$	809.34	24.6	31 %	99 %
CH^+	$1 \to 0$	835.07	0.0	0 %	50 %
CH_2	$1_{11} \to 2_{02}$	945.84	67.3	13 %	99 %
NH	$N = 1 \to 0; \; J = 2 \to 1$	974.48	0.0	0 %	96 %
H_3O^+	$0_0^- \to 1_0^+$	984.66	7.5	0 %	65 %
$H_2^{18}O$	$2_{02} \to 1_{11}$	994.63	52.9	0 %	73 %
CO	$9 \to 8$	1036.91	199.1	0 %	94 %
$H_2^{18}O$	$1_{11} \to 0_{00}$	1101.68	0.0	0 %	25 %
$H_2^{18}O$	$3_{21} \to 3_{12}$	1136.67	248.7	0 %	70 %
$H_2^{18}O$	$3_{12} \to 2_{21}$	1181.40	192.0	0 %	75 %
$H_2^{18}O$	$4_{22} \to 4_{13}$	1188.87	395.4	0 %	87 %
$H_2^{18}O$	$2_{20} \to 2_{11}$	1198.96	136.4	0 %	81 %

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observatories will be necessary to make further progress. The atmospheric opacity problem can be circumvented by observing isotopic forms of water, either HDO or $H_2{}^{18}O$. The ground-state transition of HDO has been detected (Schulz et al. 1991), but the interpretation of HDO data is difficult due to the large uncertainties in the deuterium fractionation. In contrast, fractionation effects are not expected to be important for $H_2{}^{18}O$.

Various transitions of ortho-$H_2{}^{18}O$ are observable from airborne altitudes, including the 547 GHz $1_{10} - 1_{01}$ line, although the large abundance ratio of $O^{16}/O^{18} \approx 500$ suggests that $H_2{}^{18}O$ lines will be weak. However, their interpretation should be relatively straightforward because the lines are likely to be optically thin, in contrast to the situation for $H_2{}^{16}O$. Several groups have previously searched for the 547 GHz line using the KAO but did not detect it. However, the submillimeter heterodyne receivers developed for this project have more than an order of magnitude better sensitivity than the previous instruments, and this advance has enabled us to make the first detections of the 547 GHz and 745 GHz $H_2{}^{18}O$ lines.

$H_2{}^{18}O$ observations of SgrB2 and W51

In Figure 1, we present 547 GHz spectra of SgrB2 and W51 obtained with the KAO in 1993 and 1994. Both SgrB2 and W51 have warm embedded dust cores which can serve as strong background continuum sources against which the 547 GHz ground-state transition may be detectable in absorption. Note that although the continuum is evident in both sources, we see absorption toward SgrB2 but not W51. In June 1995 we confirmed the SgrB2 detection. In addition, we solidly detected the continuum from NGC 6334, but as in W51 no absorption line was seen.

Using the Caltech Submillimeter Observatory (CSO), we have detected the 391 GHz $4_{14} - 3_{21}$ transition of ortho-$H_2{}^{18}O$ toward both Sgr B2 and W 51, at a level of $T_A^* \sim 1\text{-}2$ K (Fig. 2). The 391 GHz transition occurs between energy levels about 300 K above the ground state, and samples the gas in the dense hot cores of SgrB2 and W51 rather than their cool envelopes.

The $H_2{}^{18}O$ column density in the cool molecular envelope of SgrB2 can be estimated by calculating the apparent optical depth and integrating over velocity. Rigorously, this gives the ortho-$H_2{}^{18}O$ column density in the 1_{01} state. However, it is not difficult to show that nearly all of the ortho-$H_2{}^{18}O$ in the envelope must reside in this state, since the excitation rates due to collisions and absorption of dust continuum photons are quite small in comparison to the A-coefficient of the 547 GHz transition. We calculate the total $H_2{}^{18}O$ column density by using an ortho:para ratio of 3, which is reasonable provided that the spin excitation temperature is $T \geq 20$ K. For SgrB2, the result is $N(H_2{}^{18}O) = 1.7 \times 10^{14}$ cm^{-2}. For W51, we can only set an upper limit of $N(H_2{}^{18}O) < 3.7 \times 10^{13}$ cm^{-2}. The relative abundance of water can be determined by using maps of $C^{18}O$ emission to determine the H_2 column density. This yields $N(H_2) \approx 1.5 \times 10^{23}$ cm^{-2} and $H_2{}^{18}O/H_2 \approx 1.1 \times 10^{-9}$ for SgrB2, while
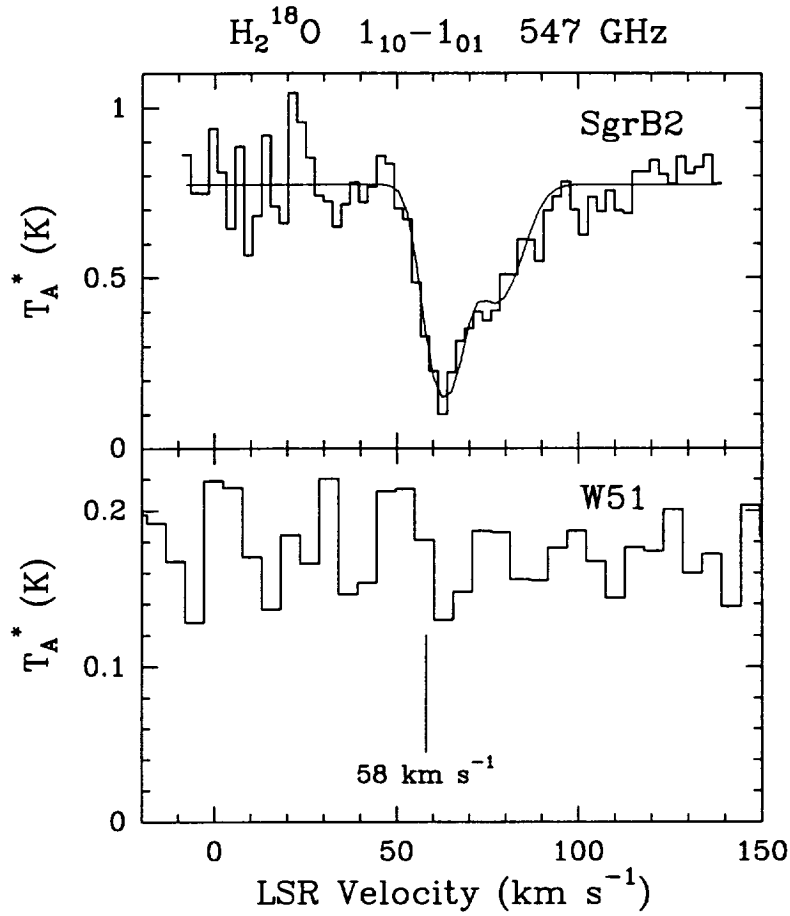
Figure 1: Observations of the 547 GHz $H_2^{18}O$ line toward SgrB2 and W51.

$N(H_2) \approx 5 \times 10^{22}$ cm^{-2} and $H_2^{18}O/H_2 < 8 \times 10^{-10}$ for W51. Using $^{16}O/^{18}O \approx 250$ for SgrB2 and 500 for W51, we obtain $H_2^{16}O/H_2 \approx 3 \times 10^{-7}$ and $< 4 \times 10^{-7}$. The overall conlusion is that H_2O abundances are quite low in cool envelopes, substantially lower than typically predicted by chemical models.

In contrast, the H_2O abundances in the hot cores are substantially larger. By analyzing our 391 GHz CSO data, and the 203 GHz IRAM 30m data of Gensheimer *et al.* (1996), we find that the 12″ beam-averaged water abundances in the cores can be estimated as $H_2O/H_2 \approx 2 \times 10^{-6}$ for SgrB2(N) and 3×10^{-5} for W51 MAIN. One possible interpretation is that the H_2O ice mantles on dust grains evaporate when subjected to radiative heating in hot cores. This mechanism is also thought to be responsible for the large NH_3 and HDO abundances in hot cores. The very low water abundances we derive for cool molecular envelopes could be due to a low abundance of H_3O^+, a small branching ratio to produce H_2O from the dissociative recombination of H_3O^+, a large abundance of destructive ions, or some other efficient H_2O removal mechanism such as freeze-out on dust grains. SOFIA

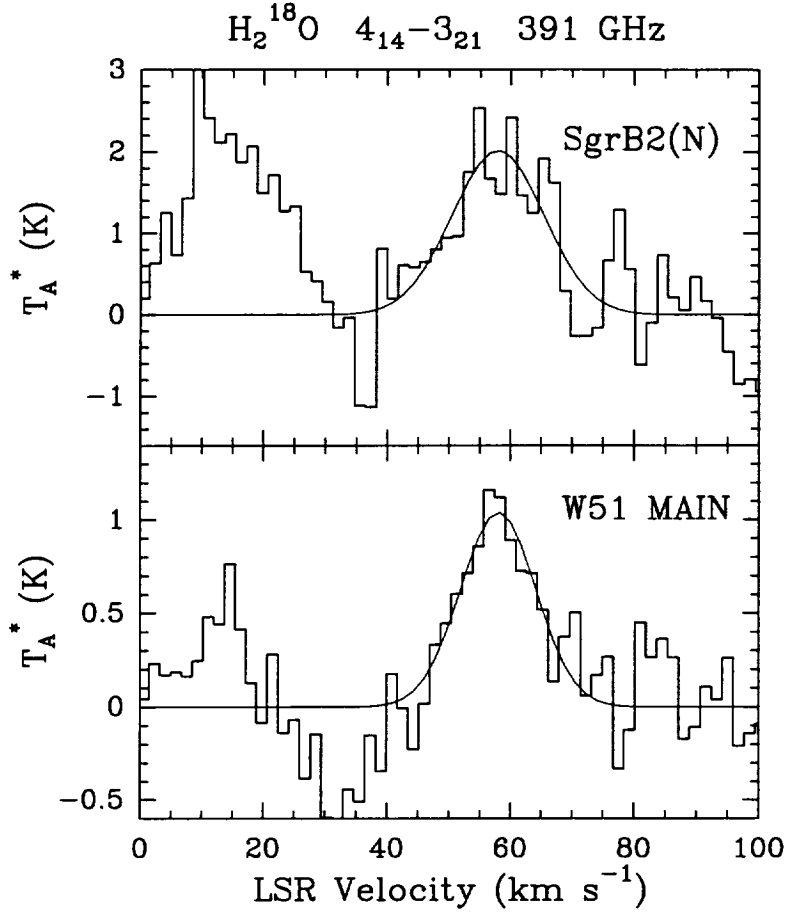Figure 2: Observations of the 390 GHz $H_2^{18}O$ line toward SgrB2 and W51.

observations of the 984 GHz ground-state line of H_3O^+ in absorption in cool envelopes could help clarify the situation.

To verify our conclusions, we performed detailed radiative transfer calculations for SgrB2(N) using the code and cloud model that we have developed. Our code iteratively solves for the radiative transfer in a dusty cloud and for $H_2^{18}O$ statistical equilibrium in 200 radial shells. Solving the radiative transfer problem for water is a non-trivial task, especially when one includes the continuum absorption and emission from dust. Our code implements recently developed techniques for calculating stellar atmospheres, and is probably the most sophisticated treatment of the radiative transfer of H_2O to date. Our cloud model has $n \sim r^{-2}$ and $T \sim r^{-0.5}$. We include 22 levels and 53 transitions for ortho-$H_2^{18}O$, and 22 levels and 56 transitions for para-$H_2^{18}O$. The model reproduces the 203, 391, and 547 GHz line intensities when the abundance in the $r < 0.2$ pc core is $H_2O/H_2 = 5 \times 10^{-6}$, and when $H_2O/H_2 = 3.3 \times 10^{-7}$ for the $r > 0.2$ pc envelope. These are quite similar to the abundances given earlier. The excitation of $H_2^{18}O$ at all radii is dominated by radiative pumping of the

far-infrared rotational transitions by the dust continuum radiation.

We have investigated the effect of H_2O on the energy balance of molecular clouds using our radiative transfer code and our Sgr B2 model. In the $r < 0.2$ pc core, the far-IR rotational transitions of H_2O appear to be nearly as effective as H_2-dust grain collisions for exchanging energy between gas and dust. In contrast, cooling by H_2O appears to play a negligible role in the energetics of the envelope, due to the low density, temperature, and H_2O abundance.
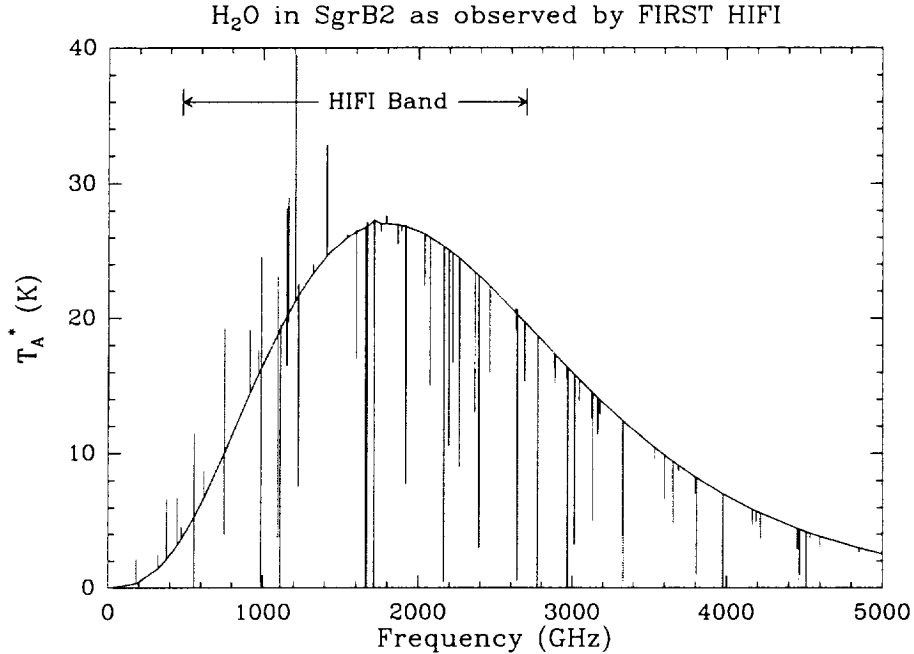

Figure 3: The predicted water spectrum of SgrB2 as observed by FIRST.

Our KAO observations of $H_2^{18}O$ and the radiative transfer model we have developed have proven very useful for understanding what other instruments or observatories may be able to observe. For instance, Fig. 3 shows how the entire H_2O spectrum of SgrB2 would appear if observed by the "HIFI" heterodyne instrument for the FIRST mission (a 3.5 m submm/FIR space telescope being developed by ESA and NASA).

$H_2^{18}O$ observations of Orion-KL

In Orion-KL, we have detected *two* $H_2^{18}O$ lines with the KAO, at 547 GHz (Fig. 4) and at 745 GHz (Fig. 5), both in February 1994. In addition, we detected the 391 GHz line using the CSO. The noise level at 745 GHz is higher than at 547 GHz since the SIS mixer we used was optimized for 550 GHz, and at 745 GHz the receiver temperature had jumped up to 860 K (DSB) (compared to 120 K at 550 GHz). The width of the main component of the 547 GHz line appears to be about $\Delta V \approx 20$ km s^{-1}, which is suggestive of the "low-velocity
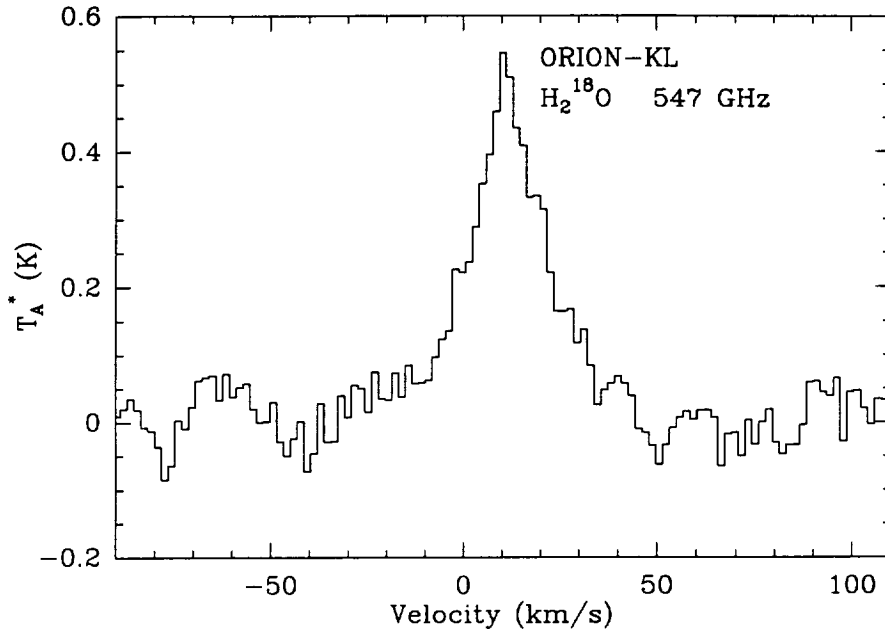
Figure 4: Detection of the $1_{10} - 1_{01}$ 547 GHz ground-state transition of ortho-$H_2^{18}O$ in Orion-KL.

outflow" that is seen in 22 GHz H_2O maser emission, as well as in other species. There may also be a second component with a broader velocity distribution which would be associated with the "high-velocity outflow" seen in CO (e.g. Fig. 1). One interpretation is that we are observing shock-excited gas, in which the physical conditions are favorable for H_2O masers, and in which the H_2O abundance may be dramatically enhanced, perhaps by three orders of magnitude. In fact, our 547 GHz observations are roughly consistent with a theoretical model for shocks in Orion (Neufeld 1992). The 745 GHz line appears to be somewhat brighter than the 547 GHz line, but this may be in part due to the smaller telescope beam at the higher frequency. The energy of the lower level in this transition is 100 K, so we are clearly observing warm gas.

Unfortunately, the interpretation of the Orion-KL $H_2^{18}O$ data is not easy. Simple schemes, such as rotation temperature plots, do not yield sensible answers for the Orion-KL $H_2^{18}O$ data, indicating that radiative transfer effects are quite important. We hope to be able to use our radiative transfer code to deal with this problem and obtain a relatively simple self-consistent model for the source. Additional data, especially with high spatial resolution, would greatly assist the interpretation. We attempted to observe the 203 GHz $H_2^{18}O$ line using the OVRO millimeter interferometer. This effort was unsuccessful since 203 GHz is outside the nominal operating band, and the receivers on only two of the six telescopes were capable of tuning to 203 GHz. The receivers are now upgraded and we may
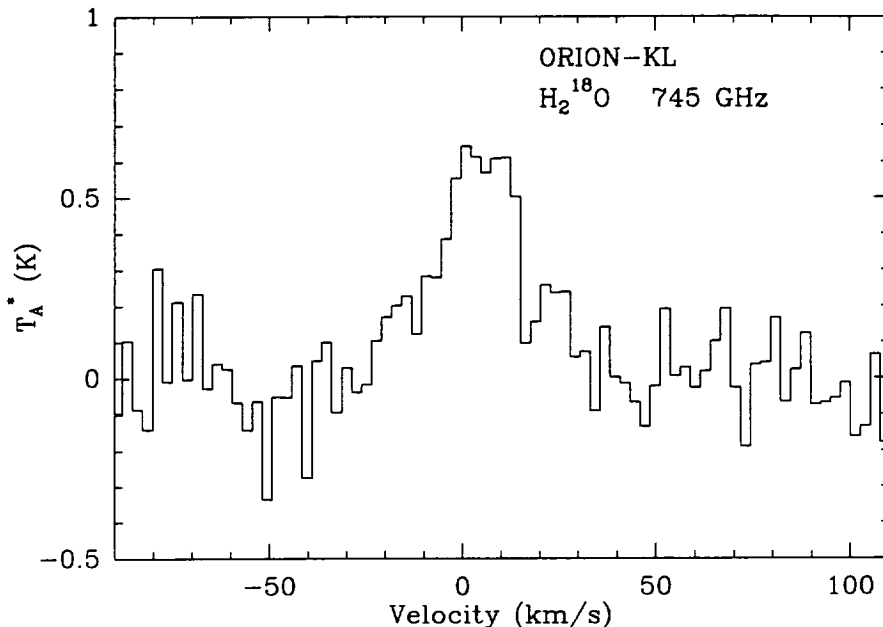
Figure 5: Detection of the $2_{11} - 2_{02}$ 745 GHz transition of para-$H_2^{18}O$ in Orion-KL. The energy of the lower level in this transition is about 100 K.

be able to try again in 1998.

2.3 HCl absorption toward SgrB2

We have also detected the 626 GHz ground-state transition of HCl in absorption toward SgrB2, during the June 1993 flight series. As in the case of $H_2^{18}O$, the line-integrated optical depth gives an estimate of the HCl column density. Detailed radiative transfer calculations were also used to verify our simple abundance estimates. Interestingly, we find that the that gas-phase chlorine must be depleted by a factor of 50-180 compared to the solar abundance, in contrast to a chlorine depletion of 2-3 found for diffuse clouds by UV absorption spectroscopy. Again, we are finding evidence for freeze-out of molecules on dust grains in the cool envelopes. These results were described in detail in a paper published in the Astrophysical Journal Letters (Zmuidzinas *et al.* 1995).

Our work on HCl in SgrB2 led to a collaborative project with Prof. David Neufeld at Johns Hopkins University, in which we proposed to use the long–wavelength spectrometer (LWS) aboard the ISO satellite to search for hydrogen fluoride (HF). The $J = 1 - -0$ line is not accessible with LWS, so we searched instead for for the $J = 2 - -1$ line at 2463 GHz. The line was detected (Neufeld *et al.* 1997), again in absorption, and was interpreted using

the radiative transfer model we developed for the $H_2^{18}O$ and HCl observations of SgrB2. The inferred HF abundance is 3×10^{-10}, which indicates a depletion of gas–phase fluorine by a factor of about 50, comparable to the chlorine depletion.

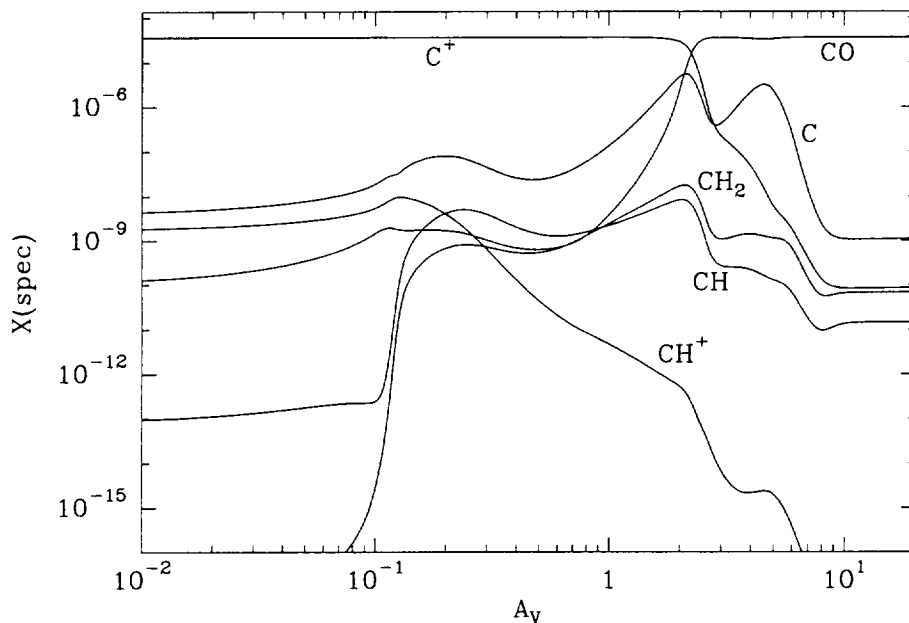## 2.4 Observations of CH at 532 and 536 GHz

Figure 6: Predicted abundances of the carbon hydrides in a photodissociation region ($n = 10^5$ cm^{-3}; $\chi_{UV} = 10^4$). Model due to Pineau des Forêts et al. 1992.

Several recent developments have renewed interest in observations of CH in molecular clouds. On the observational side, the 700 MHz lambda-doubling transitions of CH in the first rotationally excited state have been detected (Ziurys and Turner 1985; Turner 1988). These observations are puzzling because they indicate a high abundance of CH even in very dense regions, while chemical models predict CH to be abundant only in regions of low density. However, the radio data are difficult to interpret, which leads to very large uncertainties in the amount of rotationally excited CH.

On the theoretical side, it has been realized that CH may be abundant in photodissociation regions (e.g. Sternberg 1993, priv. comm.). Since C$^+$ is abundant in a PDR, the radiative association reaction C$^+$ + H$_2$ → CH$_2^+$ + hν, followed by CH$_2^+$ + e → CH + H can produce significant quantities of CH. In addition, at high temperatures CH may be produced by the endothermic reaction C$^+$ + H$_2$ → CH$^+$ + H which then leads to CH$^+$ + H$_2$ → CH$_2^+$ + H.

Once CH is produced, CH_2 follows from $CH + H_2 \rightarrow CH_2 + H$. We have computed abundances of CH, CH^+, and CH_2 in a dense ($n = 10^5$ cm^{-3}) PDR using the code of Pineau des Forêts *et al.* 1992 (Fig. 6), which clearly shows that CH and CH_2 peak near the transition from atomic to molecular gas. The total column densities in the PDR for these species is typically $2 - 5 \times 10^{13}$ cm^{-2}. This should be compared to CH column densities around 10^{14} cm^{-2} obtained from 3.3 GHz radio observations which are normally thought to sample fairly diffuse molecular gas. The observed abundance of CH^+ in diffuse clouds can approach 10^{14} cm^{-2}, which is much larger than is predicted by cloud models, and is a long-standing puzzle in interstellar chemistry that continues to attract attention. Interestingly, Duley *et al.* (1992) have recently shown that CH^+ column densities exceeding 10^{14} cm^{-2} can be produced in dense PDR's, and Snow (1993) has suggested that since UV-pumped, vibrationally excited molecular hydrogen (H_2^*) is thought to be present in PDR's, the vibrational energy may allow the reaction $C^+ + H_2^* \rightarrow CH^+ + H$ to proceed even at lower temperatures.
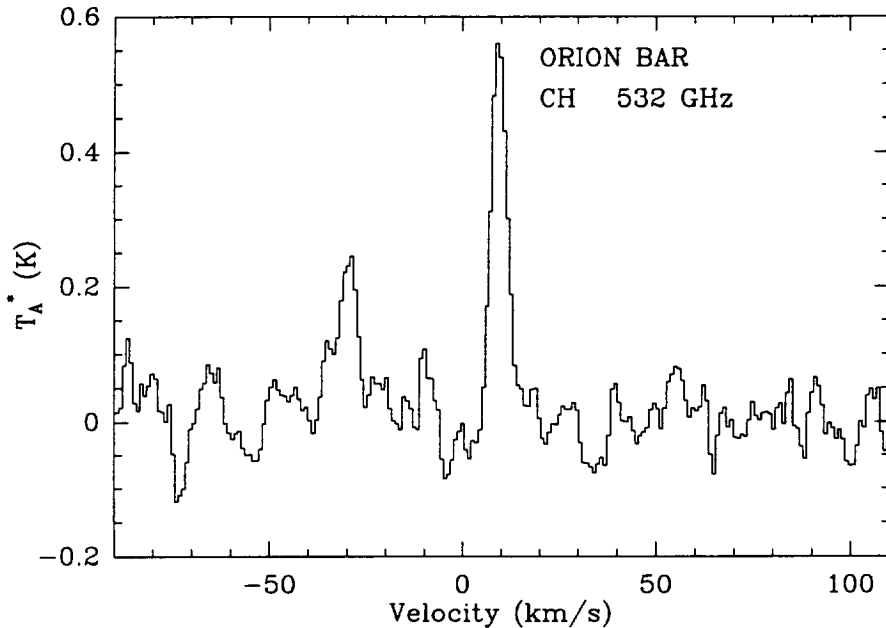
Figure 7: Detection of CH at 532 GHz toward the Orion Bar photodissociation region (February 1994).

Fortunately, as shown in Table II, all three species can be observed from airplane altitudes. We now have good detections of the ground–state rotational lines of CH at 532 and 536 GHz in a number of sources: Orion, W3, W51, and most recently in M17 (June 1995 data). The CH line is split into two components, at 532 and 536 GHz, due to lambda-doubling. In addition, each of these is split into three hyperfine components, which removes any doubt about the identification. The lines of CH^+ and CH_2 lie at 835 GHz and 946 GHz, respectively;

observations of these lines must wait for the completion of SOFIA.

Fig. 7 shows our detection of CH at 532 GHz in the well-known Orion Bar photodissociation region. Two of the three three hyperfine components overlap in frequency, which explains the two components visible in our spectrum. The intensities of the two components are in approximately the 3:1 ratio expected for optically thin emission. The 532 and 536 GHz lines of CH are very sensitive to density since $n_{cr} \approx 5 \times 10^6$ cm^{-3}. Thus, in contrast to the 3.3 GHz radio transitions, the 532/536 GHz transitions preferentially sample dense gas, and it is very likely that the emission we see arises in the dense PDR. The column density in the excited $J = 3/2$ state can be calculated directly from the line intensity, and is about 3×10^{12}, while the total CH column density is larger by rougly a factor of n_{cr}/n if $n << n_{cr}$.

2.5   Search for ^{13}CI at 809 GHz in M17

Neutral atomic carbon (C I) was first detected at 492 GHz by T. Phillips and his group in 1980, using a heterodyne receiver on the KAO. These initial results showed that in molecular clouds, neutral carbon accounted for an important fraction of the total elemental carbon abundance - neutral carbon had least 10% of the abundance of CO. In the following years, additional work on the KAO (Phillips & Huggins 1981; Keene *et al.* 1985) confirmed the initial results – neutral carbon was very abundant in molecular clouds, much more abundant than was expected, and seemed to be spread throughout the clouds rather than being confined to the cloud edges as photodissociation models had predicted. This stimulated a great deal of theoretical work on cloud models which attempted to explain the abundance of neutral carbon.

However, the 492 GHz observations can strictly set only a lower limit to the carbon abundance. One way to get a better estimate of the carbon abundance is to observe the higher excitation 809 GHz line, and compare the intensities of the 492 and 809 GHz lines to derive excitation temperatures and optical depths. This measurement was performed on the KAO in the mid-1980's (Zmuidzinas, Betz, & Goldhaber 1986). One advantage of the KAO is that it is easier to calibrate the data since the atmospheric transmission is essentially perfect. Even so, it proved difficult to get stringent limits on the neutral carbon abundance using the 492 and 809 GHz KAO data because of calibration uncertainties.

Another way to get information about the CI abundance is to search for the ^{13}C isotope. This cannot be done very well at 492 GHz, since the ^{13}CI lines turn out to be too close to the ^{12}CI line to be distinguishable in almost all sources. The situation is much better at 809 GHz - the lines are very well separated (Cooksy *et al.* 1986). However, a search for ^{13}CI requires a very sensitive receiver.

We flew a new, sensitive 800 GHz SIS receiver in June 1995, which were the first astronomical observations with an SIS receiver in this band. The receiver worked beautifully - we easily detected the ^{12}CI and CO(7-6) lines toward M17 (Fig. 8). We did not detect
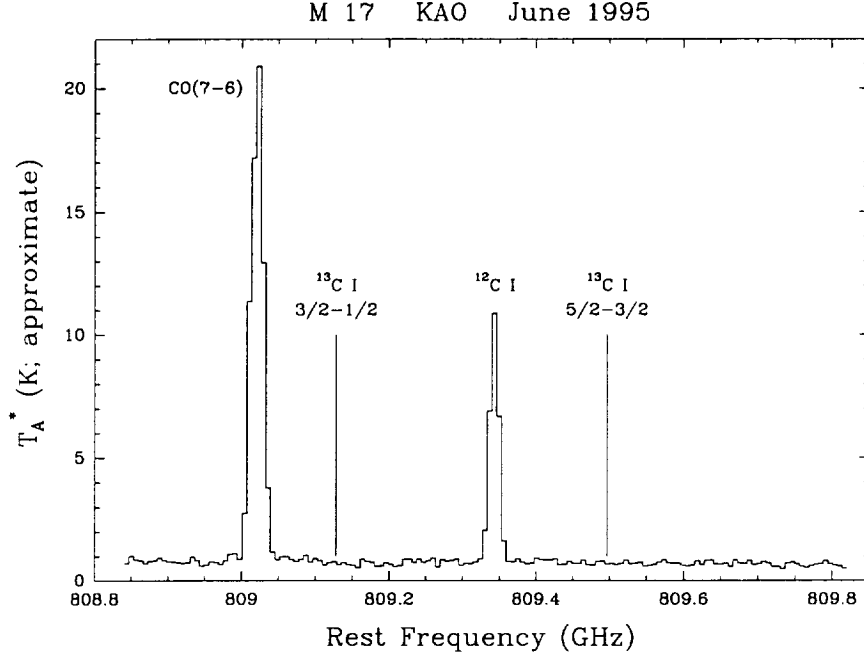
Figure 8: Search for ^{13}CI at 809 GHz in M17 (June 1995). An equivalent data set was obtained with a different LO frequency setting, to identify the sidebands, but is not included since the CO line is shifted.

the ^{13}CI line, although we should have detected the the ^{13}CI line at a 2σ level if the ^{12}CI line is optically thin and the isotopic abundance ratio is ^{12}C/^{13}C ~ 60. One possibility is that the photon-dominated chemistry in the CI region preferentially produces more ^{12}CI than ^{13}CI. Alternatively, the intrinsic isotopic ratio may be > 60. Photodissociation region models may help to sort this out – in fact, the preliminary indication is that the ^{12}CI/^{13}CI abundance ratio is expected to be *lower* than the isotopic abundance ratio (E. van Dishoeck, priv. comm.).

2.6 A Search for [C II] Emission in IRAS 10214

One of the most exciting prospects for submillimeter astronomy is the search for redshifted line emission from distant galaxies. Through the work done by the MPE-Berkeley group on the KAO (Stacey *et al.* 1991), the 158 μm [C II] line has been shown to be extremely bright, often the brightest line in the entire spectrum, and in some cases accounts for 1% of the bolometric luminosity of a galaxy. The [C II] line has also been demonstrated by the MPE-Berkeley group to be a good diagnostic of star formation activity in nearby galaxies, and hence may serve as a useful probe of the nature of distant galaxies and the origin of their luminosity.

A good target for an initial search for redshifted [C II] emission is the IRAS object FSC 10214+4724. This object is thought to be a gravitationally lensed ultraluminous infrared galaxy (Eisenhardt *et al.* 1996), with an intrinsic luminosity of $L \sim 2 \times 10^{13}\ L_\odot$. From CO and far-infrared continuum observations, it is known to contain a large quantity of molecular gas and dust, and hence at least has the fuel necessary for a giant burst of star formation activity.

Submillimeter searches for redshifted [C II] emission would generally best be done using large ground based telescopes. However, for IRAS 10124 the redshift is $z = 2.286$, and the KAO provides the only means for observing the [C II] line since the redshifted line frequency of 580 GHz is close to the 557 GHz ground–state water transition and hence is not observable from the ground.
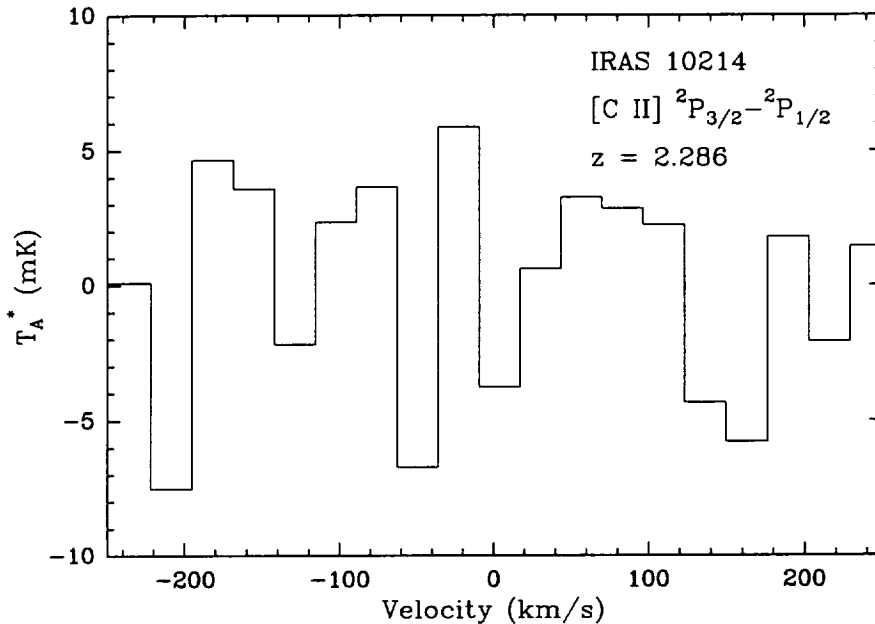

Figure 9: Search for [CII] in IRAS 10214. Integration time is 227 minutes (3.8 hr).

Figure 9 shows the spectrum resulting from our KAO observations. Scaling from the observed far-infrared flux, the [C II] line was estimated to have an apparent intensity of 3–8 mK from the KAO, and so its detection would obviously push the limits of the sensitivity and stability of our instrument. Although the line was not detected, we achieved an r.m.s. noise level of 3.9 mK per 26 km s^{-1} channel, which corresponds roughly to a 3 σ upper limit to the line intensity of 4 mK, given that the line width as observed in CO is about 250 km s^{-1}. Thus, our 3 σ upper limit is actually in the range we expected to detect the line.

No strong astronomical conclusions can be drawn at this point. However, it is clear that

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that with SOFIA's order-of-magnitude increase in collecting area, we could either detect the line with a high signal-to-noise ratio, or we would set very stringent upper limits which would show that the [C II] emission from IRAS 10214 is much weaker than from nearby galaxies.

3   SIS Receiver Technology Development

An important aspect of our program was the continuous development of superconducting (SIS tunnel junction) receiver technology. Our development effort has focused mainly on the detector, or "mixer", since this is the element in the receiver system which has the strongest influence on the sensitivity and frequency range. (For a recent review of submillimeter receiver technology, see Carlstrom & Zmuidzinas [1996] and Zmuidzinas [1997]). During our initial flight series in September 1992, our instrument was only capable of observing in the 500–580 GHz frequency band, with a sensitivity around 500 K DSB. By our 1995 flight series, the frequency range had been pushed over 800 GHz, and the sensitivity at 500 GHz was better than 100 K DSB. Laboratory developments since then have pushed the upper frequency limit over 1000 GHz.
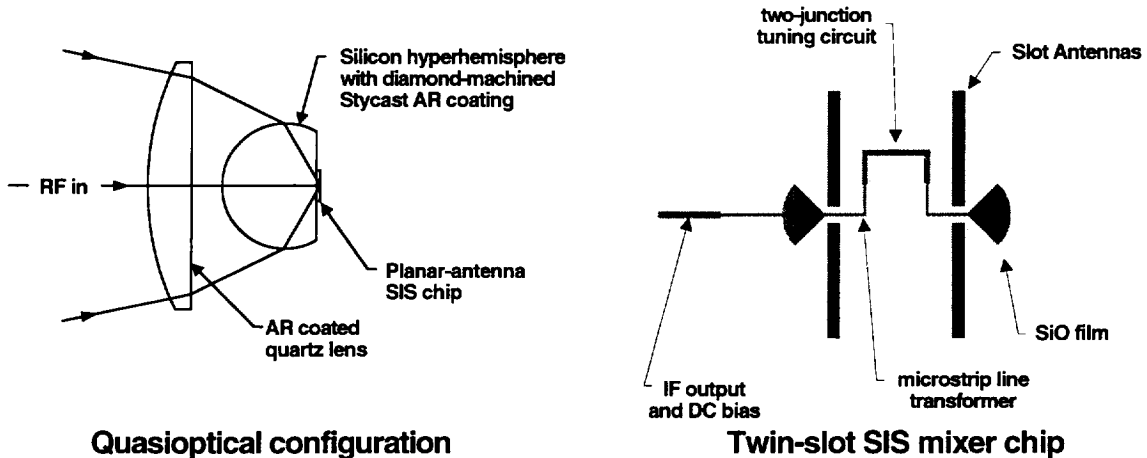

Quasioptical configuration   **Twin-slot SIS mixer chip**

Figure 10: Diagrams of our quasi–optical slot antenna SIS mixer design. The diagram on the left shows the optical configuration, including the anti–reflection coated silicon hyperhemispherical lens. The diagram on the right shows the design of the SIS chip, including the twin–slot antenna and two–junction tuning circuit.

The primary factor which motivates the use of superconducting tunnel junction (SIS) mixers in millimeter and submillimeter heterodyne receivers is that the sensitivity of these devices is in principle limited only by the uncertainty principle of quantum mechanics. Expressed as an equivalent noise temperature, the quantum limit is $T_{ql}(\text{SSB}) = h\nu/k_B$, or 0.05 K/GHz. In practice, the major challenges are to obtain good coupling of the radiation

to the micron–size junction, and to provide an inductive tuning circuit which compensates for the significant capacitance of the tunnel junction.

Over the past decade, our group at Caltech has developed novel solutions to these problems, which are documented in the publication list in the following section. The radiation coupling problem was solved by combining quasi–optical coupling using twin–slot antennas (Zmuidzinas & LeDuc 1992), two–junction tuning circuits for resonating the junction capacitance (Zmuidzinas *et al.* 1994), and diamond machined anti–reflection coatings for silicon hyperhemispherical lenses (Zmuidzinas *et al.* 1995a). We performed extensive experimental characterization of our mixers and compared the results to model calculations (Gaidis *et al.* 1996) to verify and optimize our designs. We developed normal–metal aluminum tuning circuits to extend the upper frequency limit past 1000 GHz (Bin *et al.* 1996), well past the superconducting gap frequency of 700 GHz for niobium. As a result, the noise temperatures achieved with our quasi–optical mixers are comparable or superior to the best results yet achieved with any heterodyne mixers in the 400–1100 GHz range, and give us an excellent starting point for the development of instruments for SOFIA and FIRST.

4   List of Publications

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