Spectroscopic Opportunities for SOFIA

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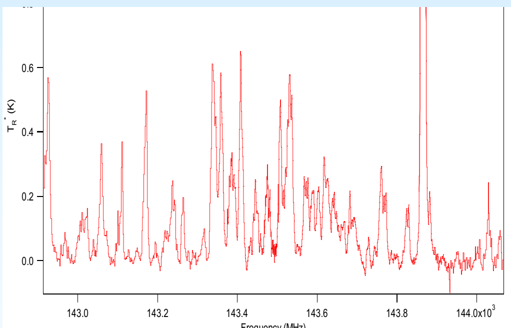

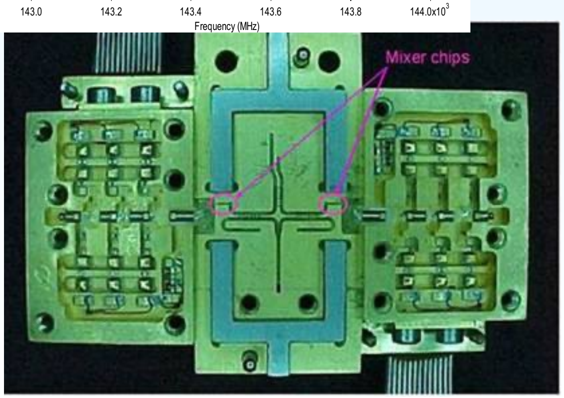

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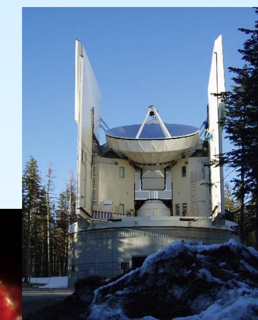
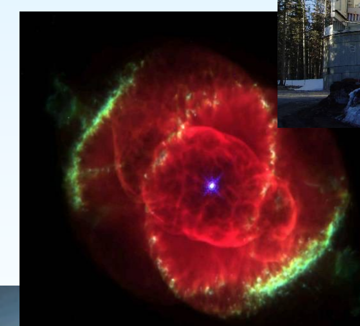
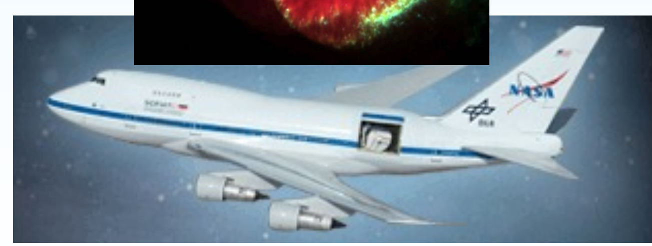






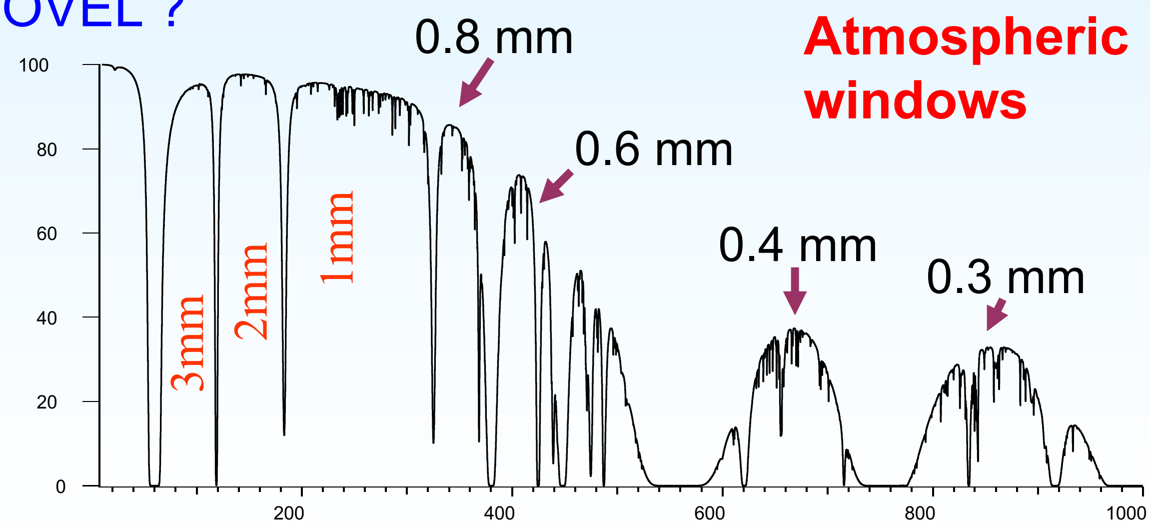
Molecular Astrophysics at SOFIA ?

- Molecular astrophysics began in 1970
- Led to discovery of ~145 different interstellar molecules
- Regime of ground based ***millimeter astronomy***

  ⇒ 1 mm (200 – 300 GHz), 2 mm (125 – 180 GHz), and 3 mm (65 -115 GHz)
- Molecular line observations

  ⇒ Major contributor to understanding of dense interstellar medium
- What can SOFIA do that is NOVEL ?

- Heterodyne receivers:
  - L1: 1.25 – 1.5 THz
  - L2: 1.8 – 1.92 THz
  - 2.4 – 2.7 THz; ~ 4.7 THz
  - Future projects
- Beam ~ 16”



SOFIA Community Task Force — May 12, 2010

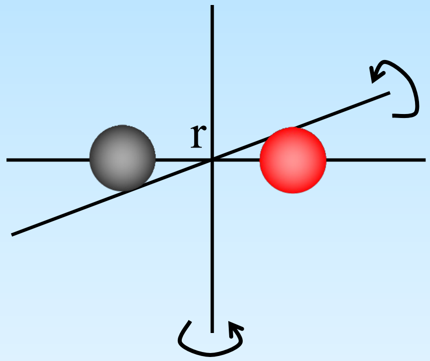
Known Interstellar Molecules

2		3		4	5	6	7	8	9	10
H_2	CH^+	H_2O	C_3	NH_3	SiH_4	CH_3OH	CH_3CHO	CH_3CO_2H	CH_3CH_2OH	
OH	CN	H_2S	HNC	H_3O^+	CH_4	NH_2CHO	CH_3NH_2	HCO_2CH_3	$(CH_3)_2O$	CH_3COCH_3
SO	CO	SO_2	HCN	H_2CO	CHOOH	CH_3CN	CH_3CCH	CH_3C_2CN	CH_3CH_2CN	$CH_3(C\equiv C)_2CN$
SO^+	CS	NNH^+	CH_2	H_2CS	$HC\equiv CCN$	CH_3NC	CH_2CHCN	C_7H	$H(C\equiv C)_3CN$	$(CH_2OH)_2$
SiO	C_2	HNO	NH_2	HNCO	CH_2NH	CH_3SH	$H(C\equiv C)_2CN$	H_2C_6	$H(C\equiv C)_2CH_3$	
SiS	SiC	CCS	HOC^+	HNCS	NH_2CN	C_5H	C_6H	CH_2OHCHO	C_8H	
NO	CP	NH_2	NaCN	CCCN	H_2CCO	HC_2CHO	$c\text{-}CH_2OCH_2$		C_8H^-	**11**
NS	CO^+	H_3^+	MgNC	HCO_2^+	C_4H	$CH_2{=}CH_2$	$H_2CC(OH)H$		CH_3CONH_2	$H(C\equiv C)_4CN$
HCl	HF	NNO	AlNC	CCCH	$c\text{-}C_3H_2$	H_2C_4	C_6H^-			
NaCl	SH	HCO	SiCN	$c\text{-}C_3H$	CH_2CN	HC_3NH^+				**12**
KCl	HD	HCO^+	SiNC	CCCO	C_5	C_5N				
AlCl	PO	OCS	H_2D^+	C_3S	SiC_4					**13**
AlF	AlO	CCH	MgCN	HCCH	H_2C_3					$H(C\equiv C)_5CN$
PN		HCS^+	KCN	$HCNH^+$	HCCNC					
SiN		c-SiCC	HCP	HCCN	HNCCC					
NH		CCO	CCP	H_2CN	H_2COH^+					
CH		AlOH	PH_3	$c\text{-}SiC_3$	C_4H^-					

~100 Carbon Molecules
11 Silicon Species
10 Metal Containing Molecules
6 Phosphorus Species

~ 90% Identified by Radio Astronomy

Molecules Unique to Sub-mm and Far IR



- Interstellar Molecular Gas is **COLD** (T ~ 10 -100 K)
- **Rotational Levels** predominantly populated
  - ⇒ two-body **collisions** with H_2
- **Spontaneous Decay** results in **narrow emission lines**
- Rotational Transition **Frequencies**
  - ⇒ proportional to ***moments of inertia***

$$\nu = 2B\,(J+1)$$

$$B = \frac{\hbar}{2I} \qquad I = \mu\, r^2$$

⇒ Atomic Mass, Bond Lengths, Bond Angles

- Rotational Spectrum is "Finger Print" Pattern
- Unique to a Given Chemical Compound
- Allows for ***unambiguous*** identification

- Light molecules with small I
- ⇒ Large rotational constants
- ⇒ Spectrum in sub-mm, far IR
- "Light" = ***HYDRIDES***

What we know about hydrides…

- Chiefly from Ground-based Observations

Known Interstellar (Diatomic) Hydrides		
Hydride	**Detection Method**	**THz Transitions**
CH	Optical, cm λ-doubling, THz	N = 2 – 1; λ-doubling, hyperfine: 1.47 THz
OH	cm λ-doubling, THz	J = 3/2 – ½; λ-doubling, hyperfine: 2.51 THz
NH	Optical	N = 1 – 0; fine structure/hyperfine: 1.0 THz
SH	IR	J = 3/2 – ½; λ-doubling, hyperfine: 1.38 THz
HCl	Sub-mm	J = 2 – 1; quadrupole hyperfine: 1.25 THz
HF	THz (ISO)	J = 1 – 0: 1.23 THz
CH^+	Optical	J = 2 – 1: 1.67 THz
H_3O^+	Sub-mm	$J(K_a, K_c)$ = 0(0,0) –1(0,1): 0.98 THz $J(K_a, K_c)$ = 2(0,0) –1(0,1): 2.97 THz
H_2D^+	Sub-mm	$J(K_a, K_c)$ = 1(0,1) –0(0,0): 1.37 THz $J(K_a, K_c)$ = 2(1,1) –2(1,2): 1.11 THz

Arizona Radio Observatory

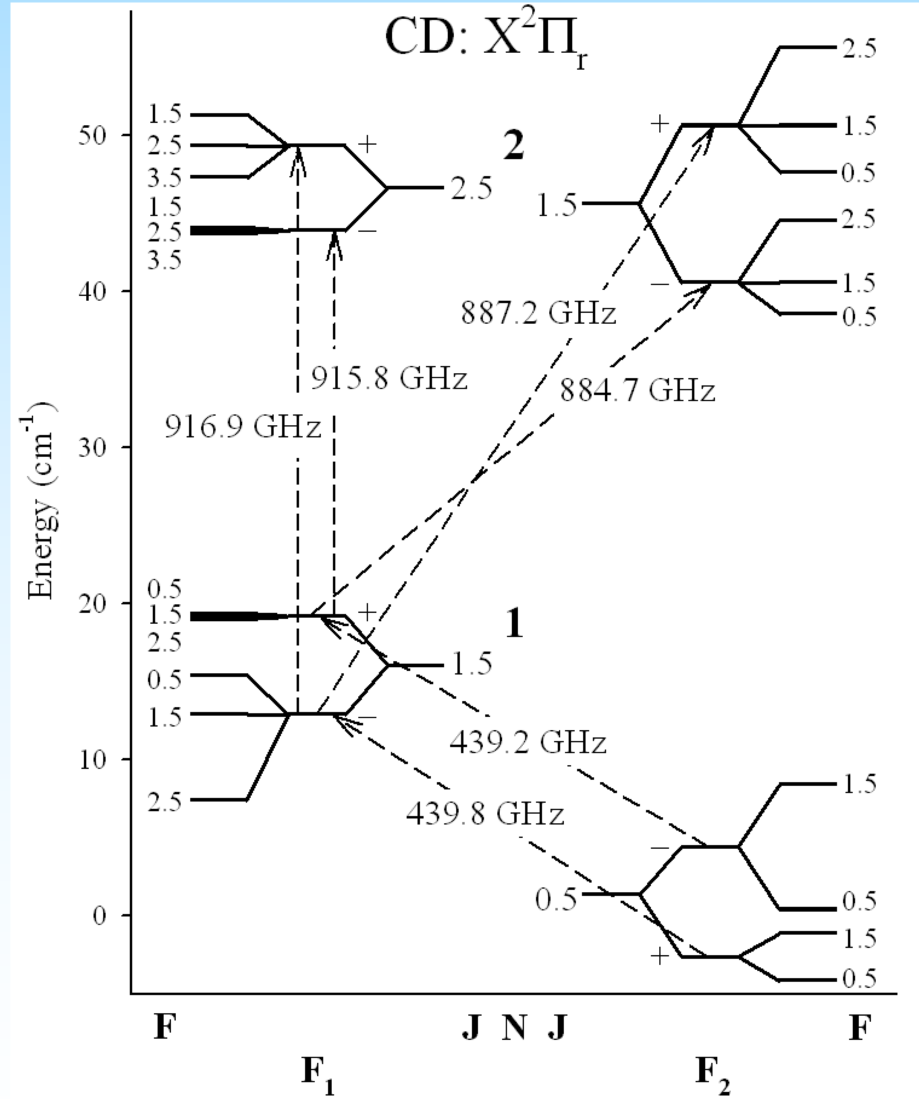
- Chance sub-mm transitions observable from ground
- OH, CH, SH etc have $^2\Pi$ ground electronic states

⇒ **Lambda-doubling** transitions at cm wavelengths

- Electronic transitions in optical, UV
- Perhaps not always best methods for studying hydrides

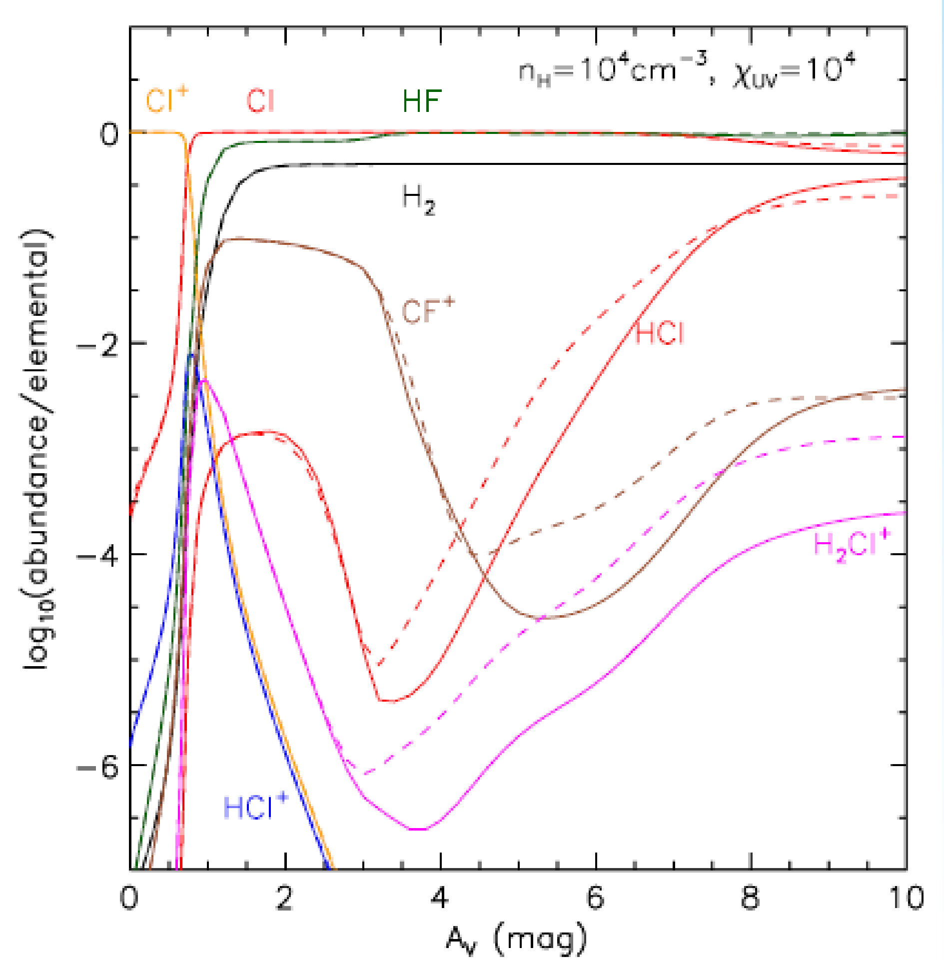
⇒ *Very selective*

- More useful to study pure rotational transitions in THz region



Importance of Hydrides

- Fundamental building blocks of Interstellar Chemistry
- Ubiquitous presence in dense and diffuse clouds
- **Important coolants** in dense gas
  $\Rightarrow$ large Einstein A's
- Trace **elemental** compositions
- Observations really lacking !!
- CH^+, NH only observed optically
- One observation of SH
- Limited data on THz OH, CH



Neufeld &Wolfire

$\Rightarrow$ COMMON Hydrides Unexplored

Specialty Molecules

Species	Ground State	Estimated B (MHz)*	THz Transitions
SiH	$^2\Pi_r$	221,590	J = 5/2 – 3/2; 1.2 THz
PH^+	$^2\Pi_r$	251,429	J = 5/2 – 3/2; 1.4 THz
AlH^+	$^2\Sigma^+$	201,938	N = 3 – 2; 1.2 THz
CrH^+	$^5\Sigma^+$	199,840	N = 3 -2 1.1; THz
TiH	$^4\Phi_r$	160,749	J = 7/2 – 5/2; 1.1 THz
TiH^+	$^3\Phi_r$	174,768	J = 3 – 2; 1.04 THz
FeH	$^4\Delta_i$	202,181	J = 9/2 – 7/2; 1.8 THz
FeH^+	$^5\Delta_i$	198,665	J = 11/2 – 9/2; 2.1 THz
MgH^+	$^1\Sigma^+$	188,050	J = 3 -2; 1.2 THz

* FREQUENCIES NOT AVAILABLE

Relevance of "Specialty Molecules"

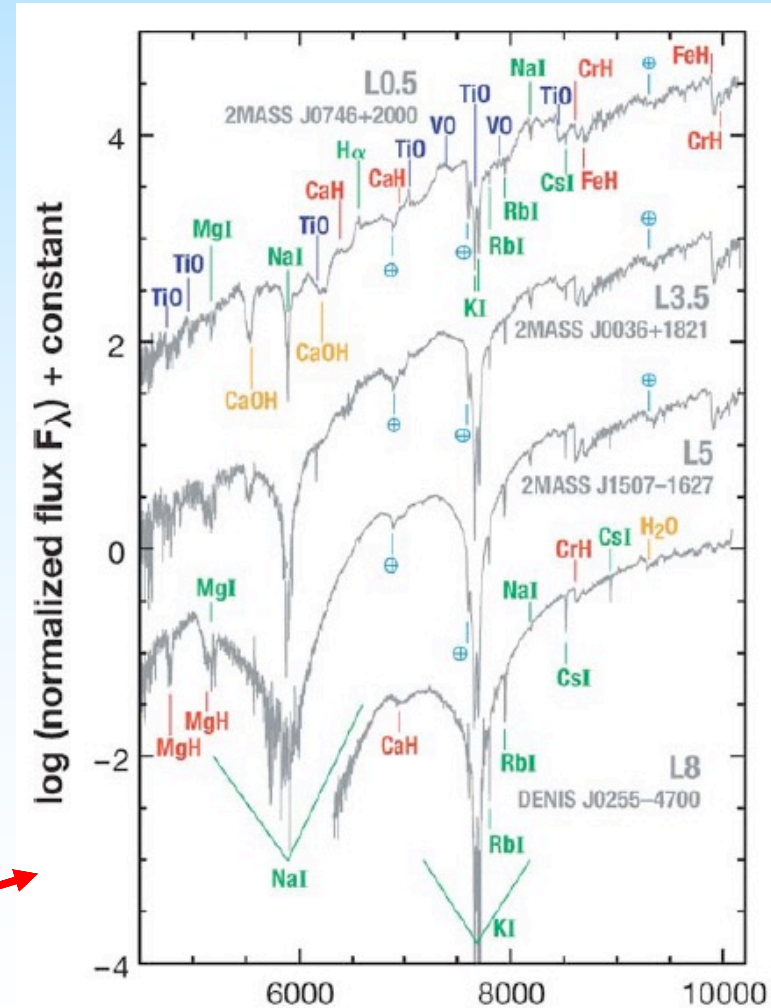
- Abundant in atmospheres of M, S, and L stars (CrH, FeH, MgH, CaH)
- Important in latest sub-dwarfs (T type "pseudo" planets)

⇒ Shift from metal oxides to metal hydrides dramatic

- Implications for planetary atmospheres
- Novel connection between photospheric and circumstellar envelope material

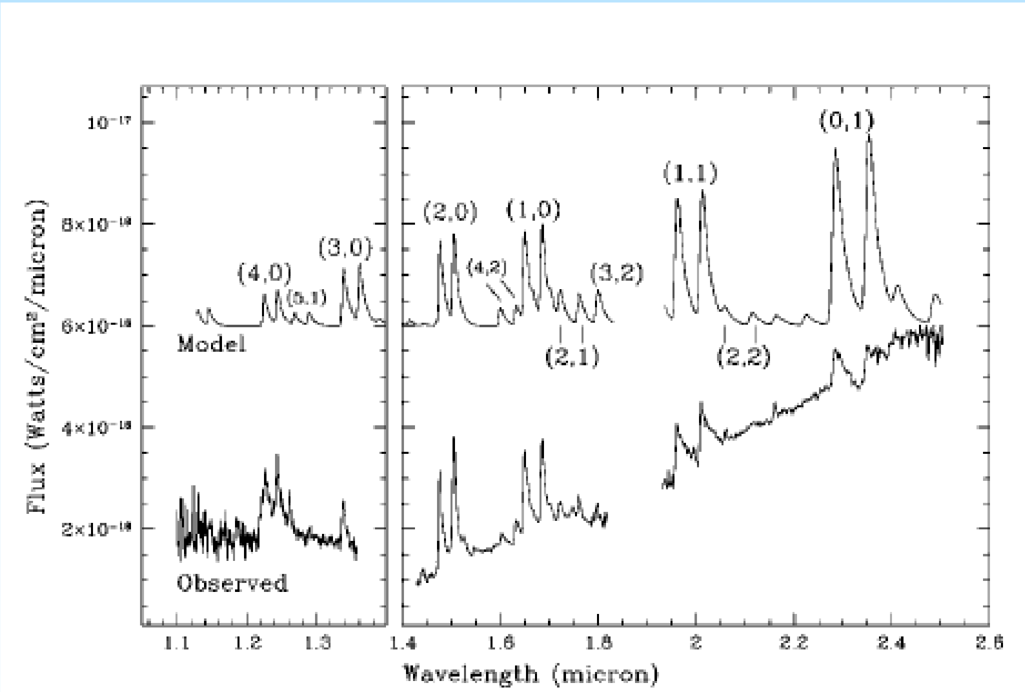
⇒ Known circumstellar refractory species

- Tracers of grain condensation

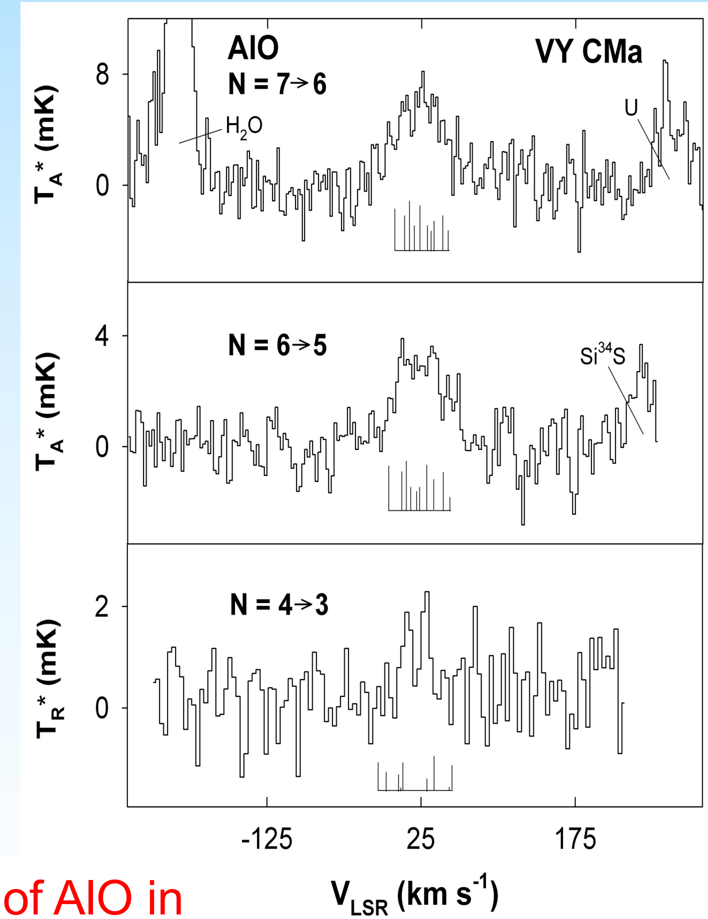


L, T dwarf spectra

Connecting photospheric and circumstellar material….



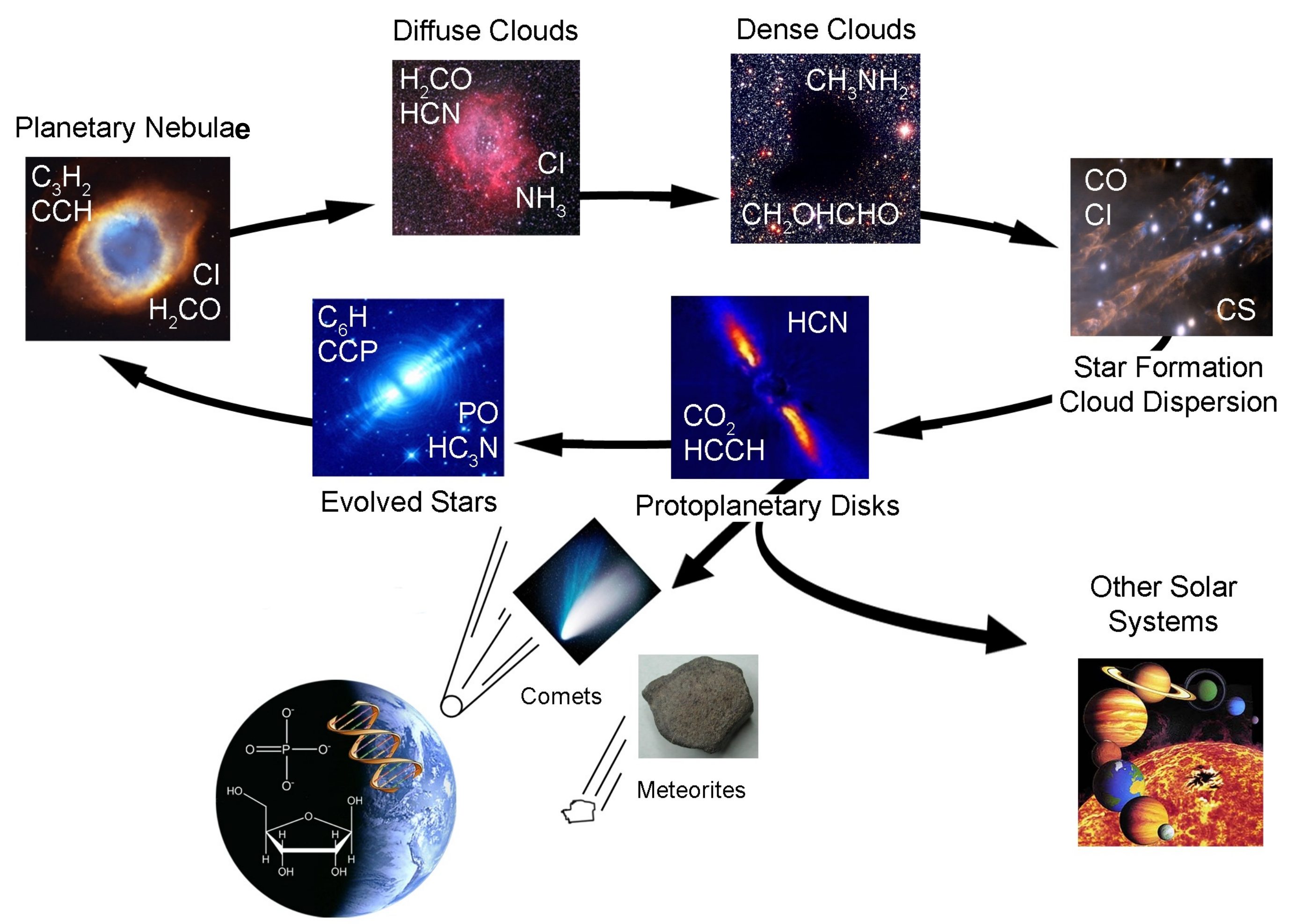
$A^2\Pi$- $X^2\Sigma$ transition of AlO
V4332 Sgr
M-type Giant/Supergiant
(Banerjee et al. 2003)



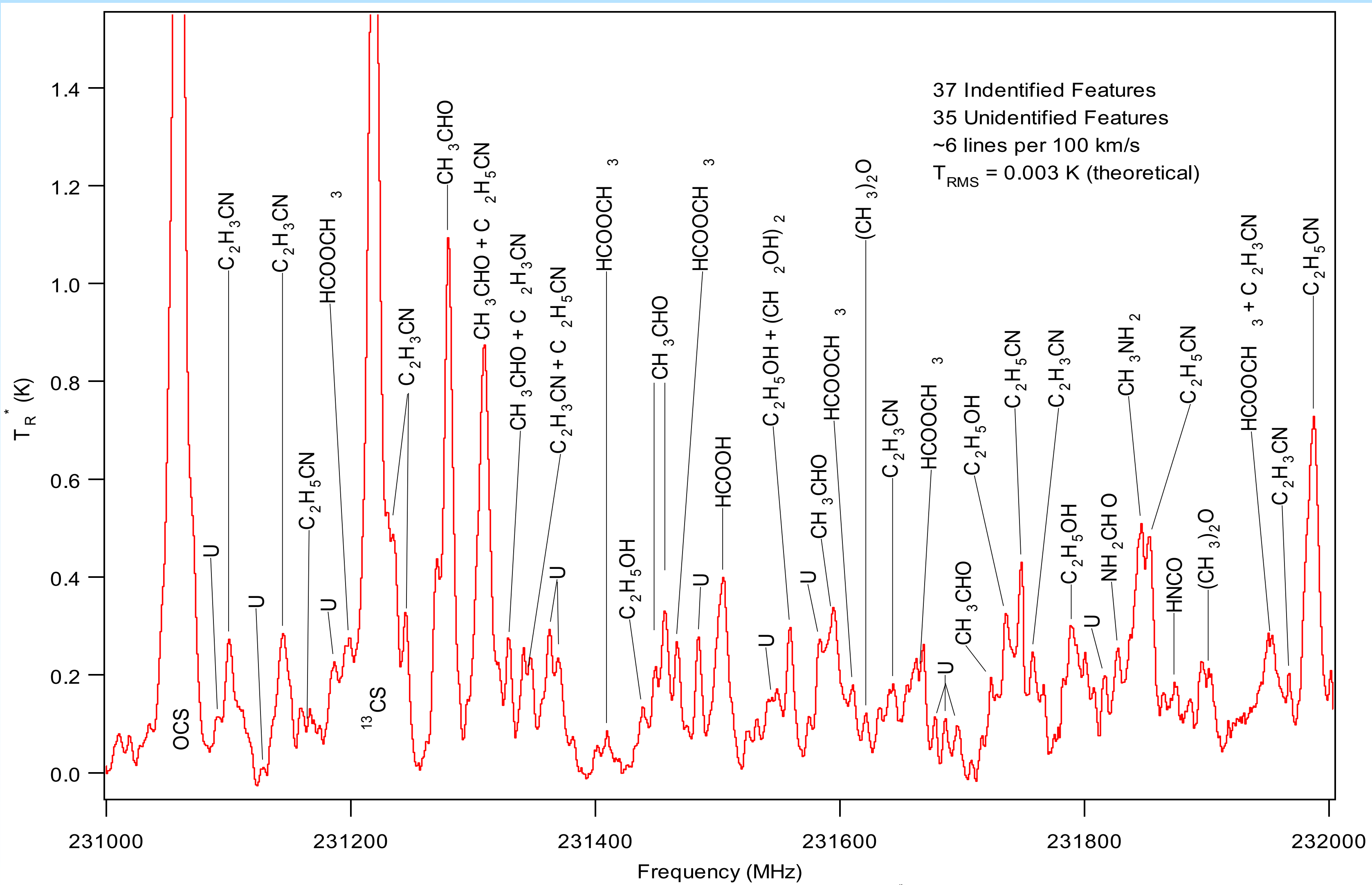
Mm transitions of AlO in Supergiant VY Canis Majoris (Tenenbaum & Ziurys 2009)

Cycling of Molecular Material in Interstellar Space

- **Where to study hydrides ??**
- **Molecules** cycled through interstellar space
- Many interesting sources.....

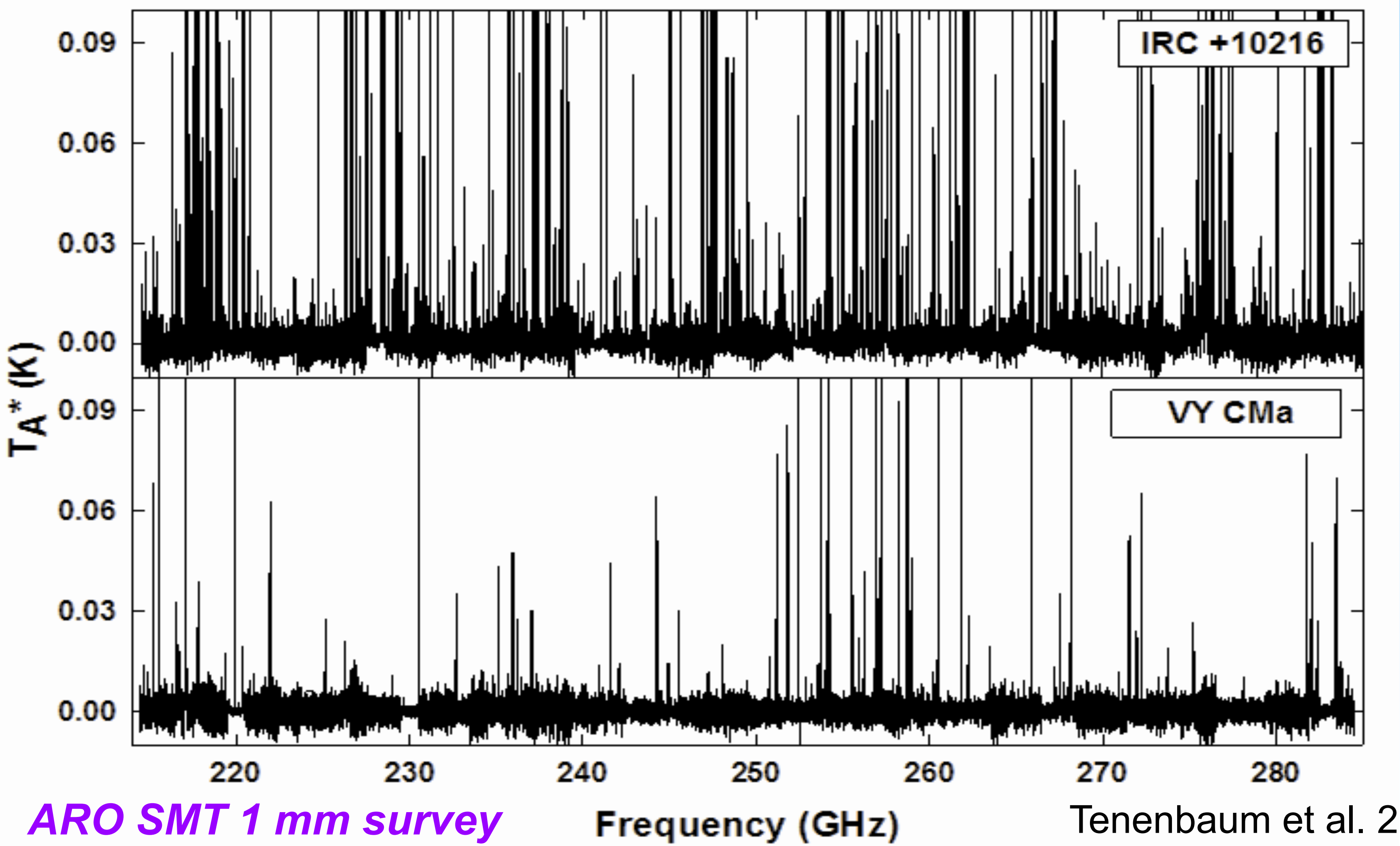


Molecular Clouds…



Where does excitation drop off ?

Circumstellar Envelopes of Evolved Stars…



ARO SMT 1 mm survey

Tenenbaum et al. 2010

Arizona Radio Observatory

Comparative Survey of O vs. C rich circumstellar gas

•Region Measured:

210 - 285 GHz

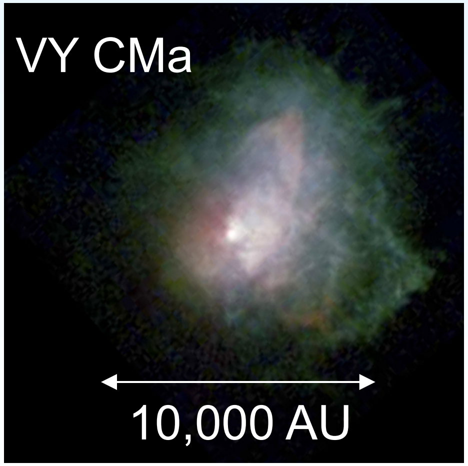
(75 GHz)

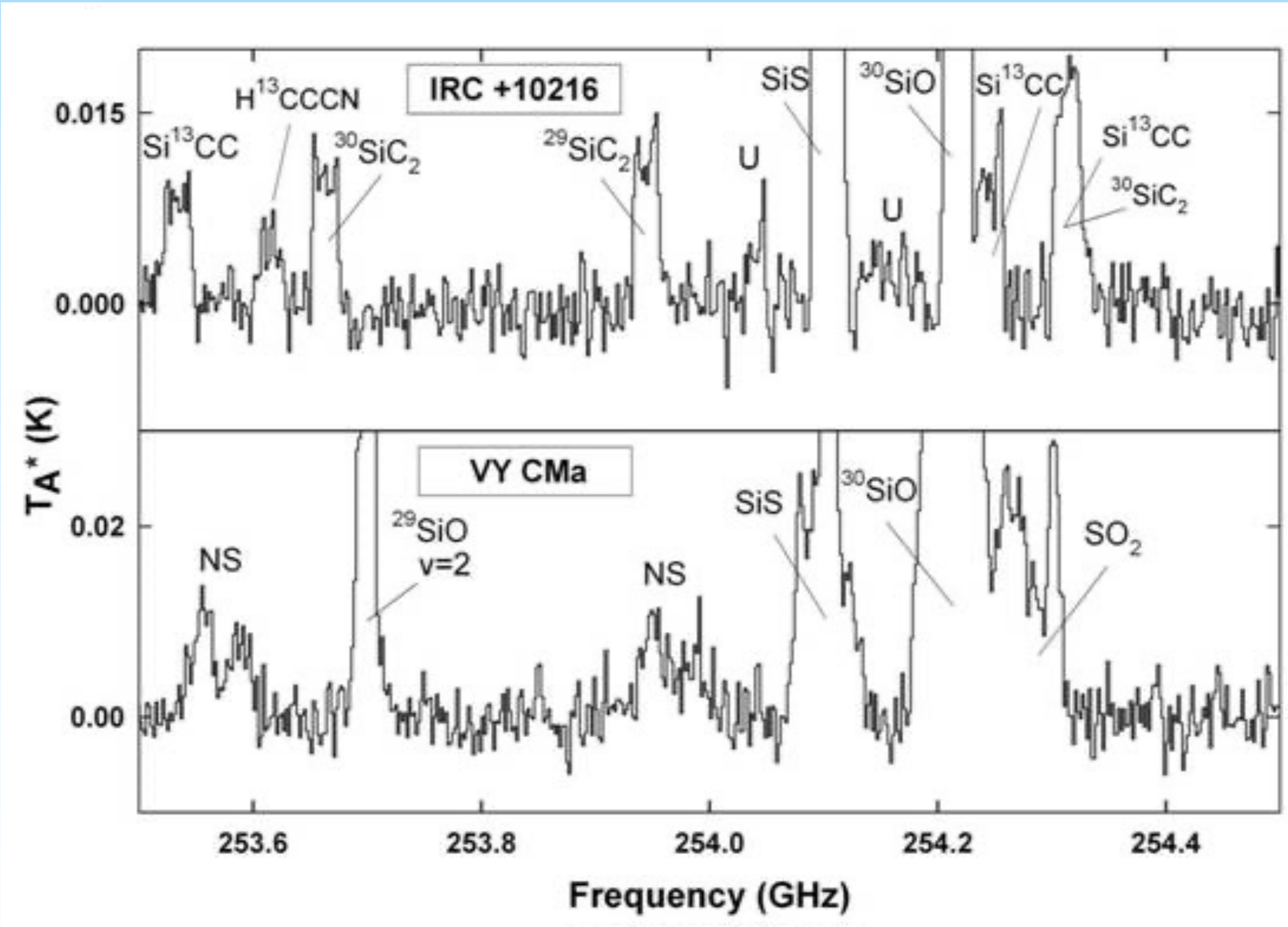
• **IRC+10216:**

- 615 lines total
- 128 unidentified

• **VY Canis Majoris:**

- 203 lines total
- 14 unidentified



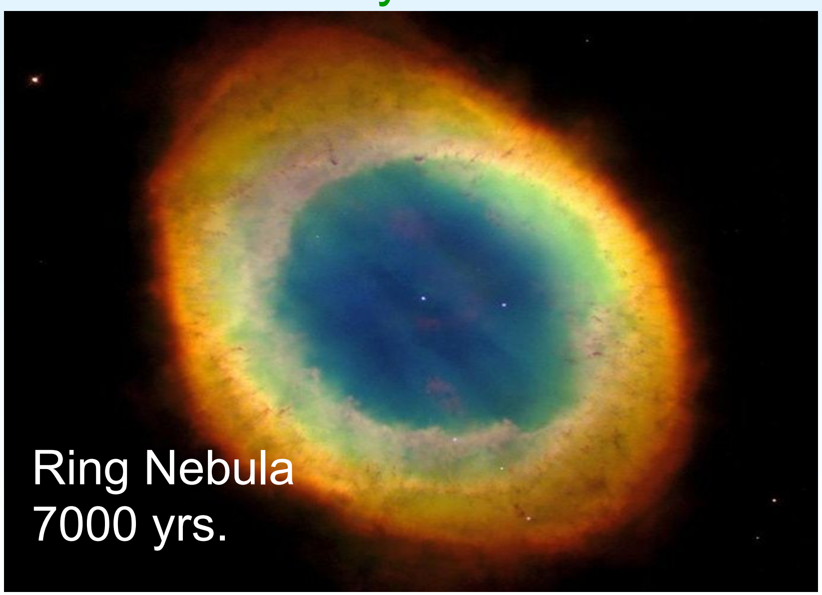


• ***Excellent sources for common and "specialty" Hydrides***

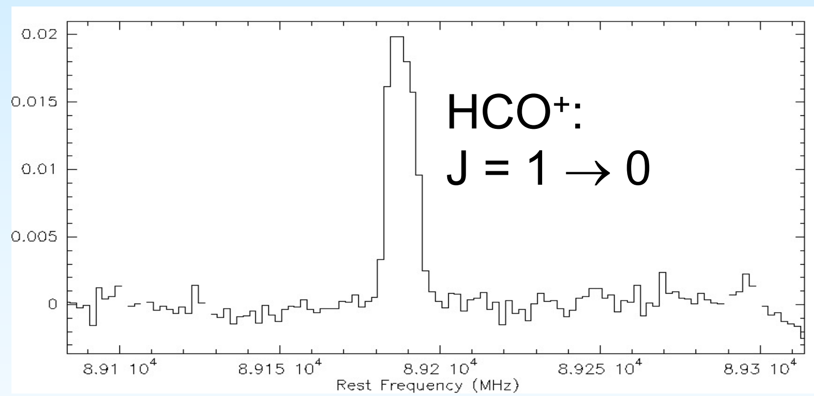
Planetary Nebulae…

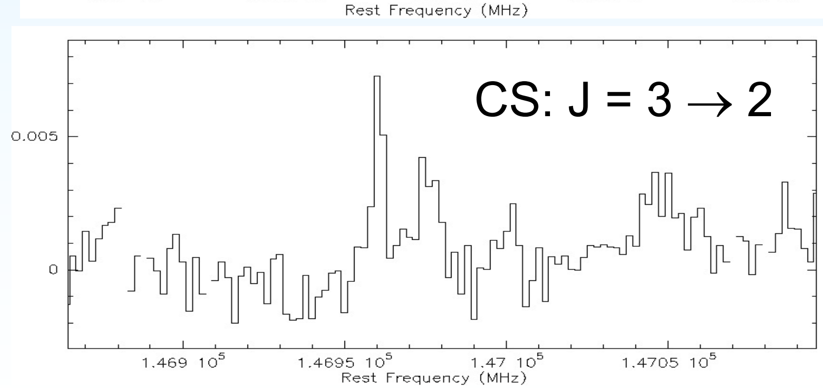
- **AGB stars** evolve into planetary nebulae (PNe)
- Central star becomes white dwarf: **HOT** (T ~ 100,000 K) **UV emitter**
- Most of original stellar mass flows into ISM on timescales of 10,000 yrs.
- Fate of Molecular Circumstellar Shell ?

⇒ Molecules in Middle-Aged to Old Planetary Nebulae



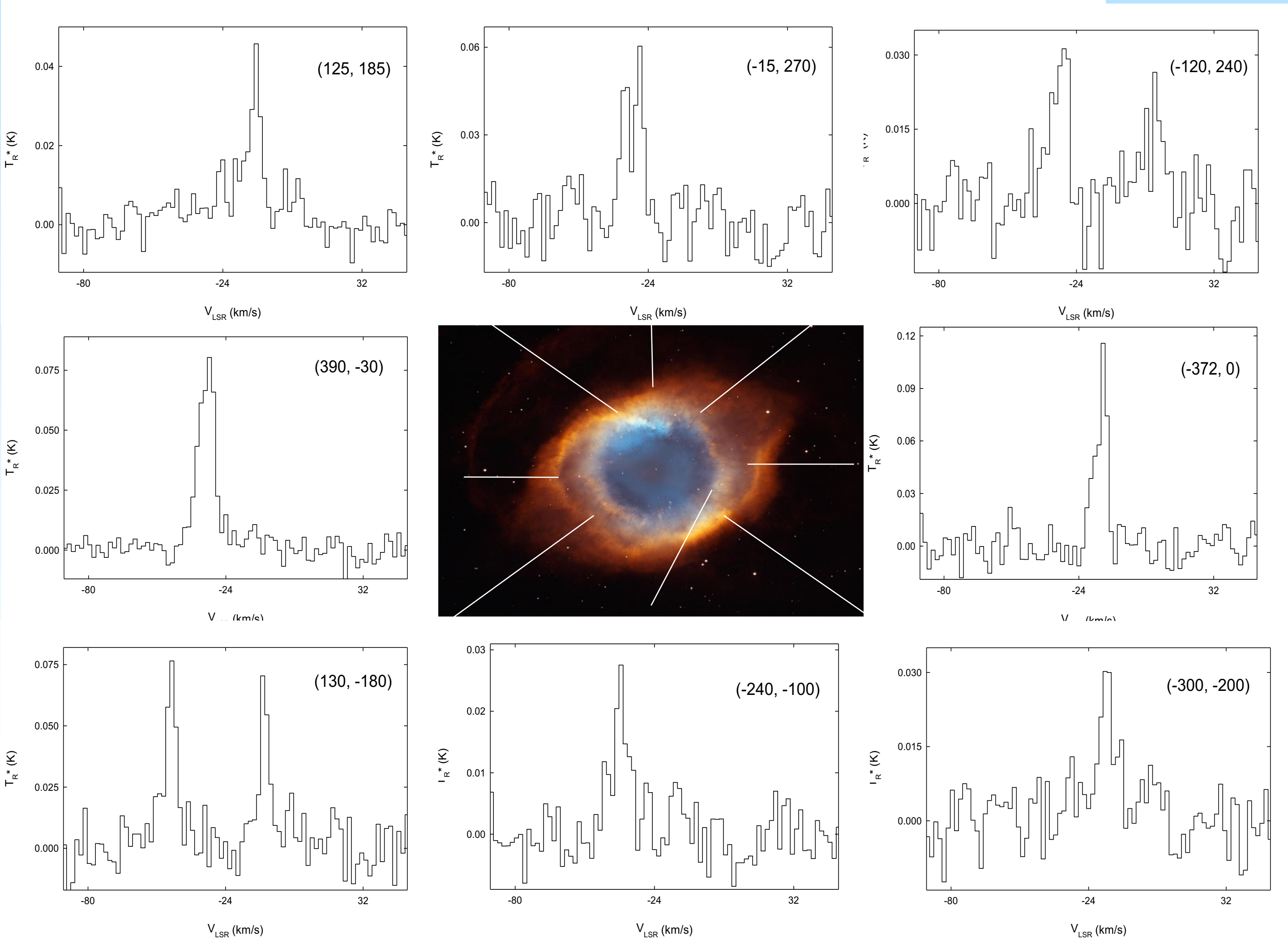
Ring Nebula
7000 yrs.





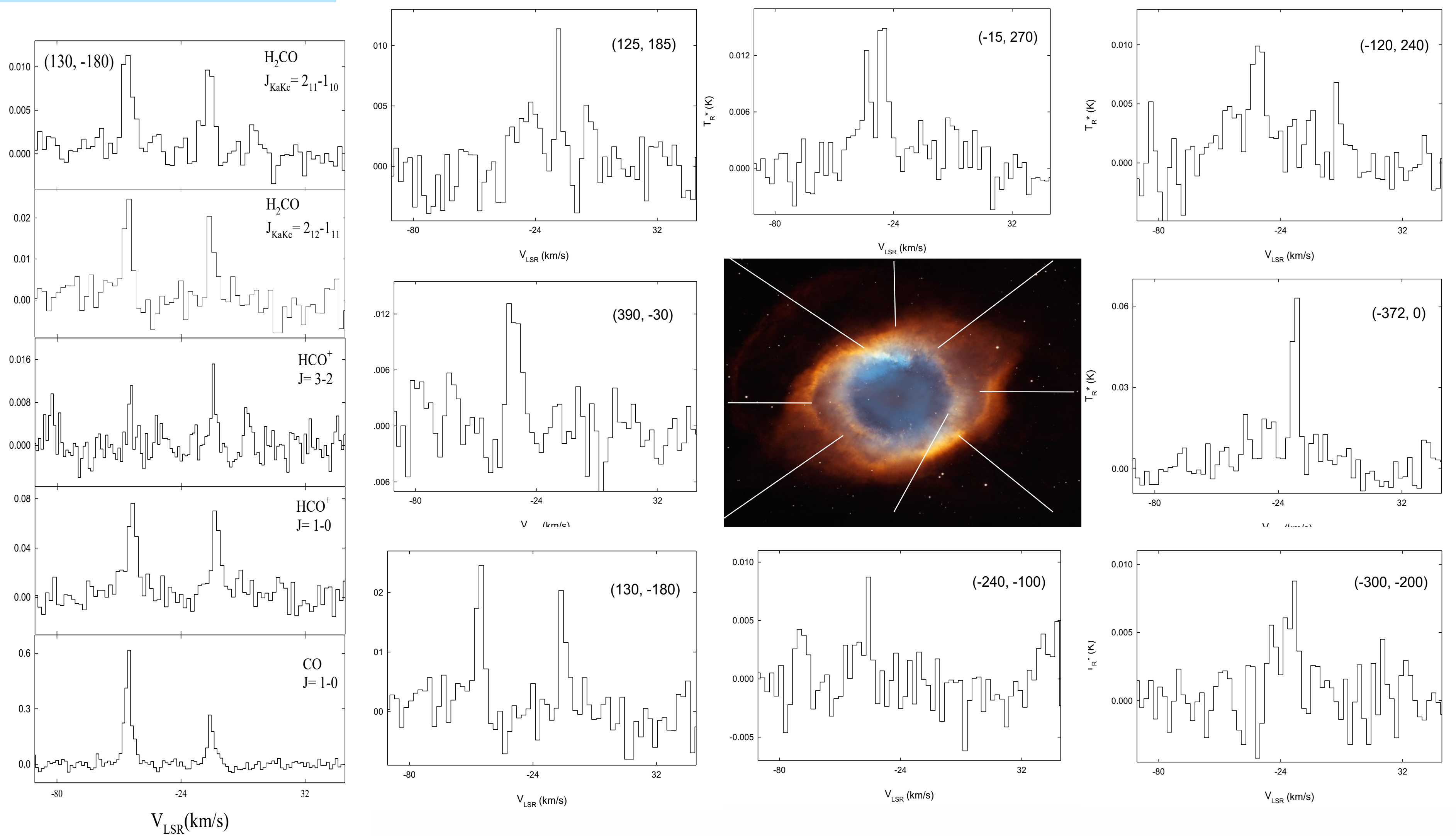
The Helix Nebula at 12,000 yrs.

HCO^+: J = 1 → 0



Y-scale: T_R*(K)

H_2CO: $J_{Ka,Kc} = 2_{12}-1_{11}$



Molecule Survival in Old Planetary Nebula

- In addition to CO, H_2CO and HCO^+:

HCN, HNC, CN seen in Helix (Bachiller 1997)

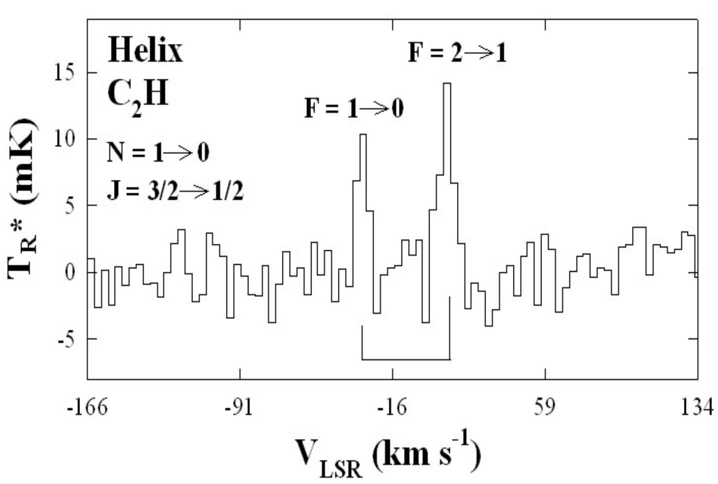
⇒ ***CCH and C_3H_2*** in the Helix

⇒ Observed with ARO 12 m (Tenenbaum et al.)

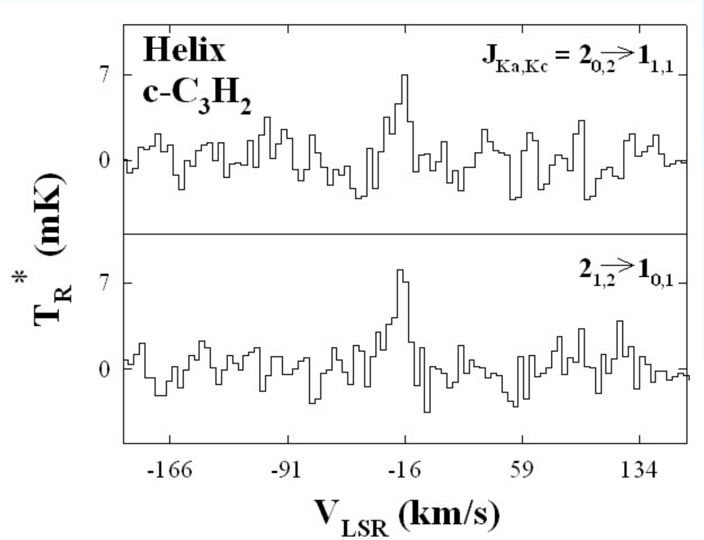
- H_2CO lines indicate ***$n \sim 3 \times 10^5$ cm^{-3}***

⇒ ***MOLECULES SURVIVING in SELF-SHIELDING CLUMPS***

(Howe et al. 1994; Redman et al. 2003)



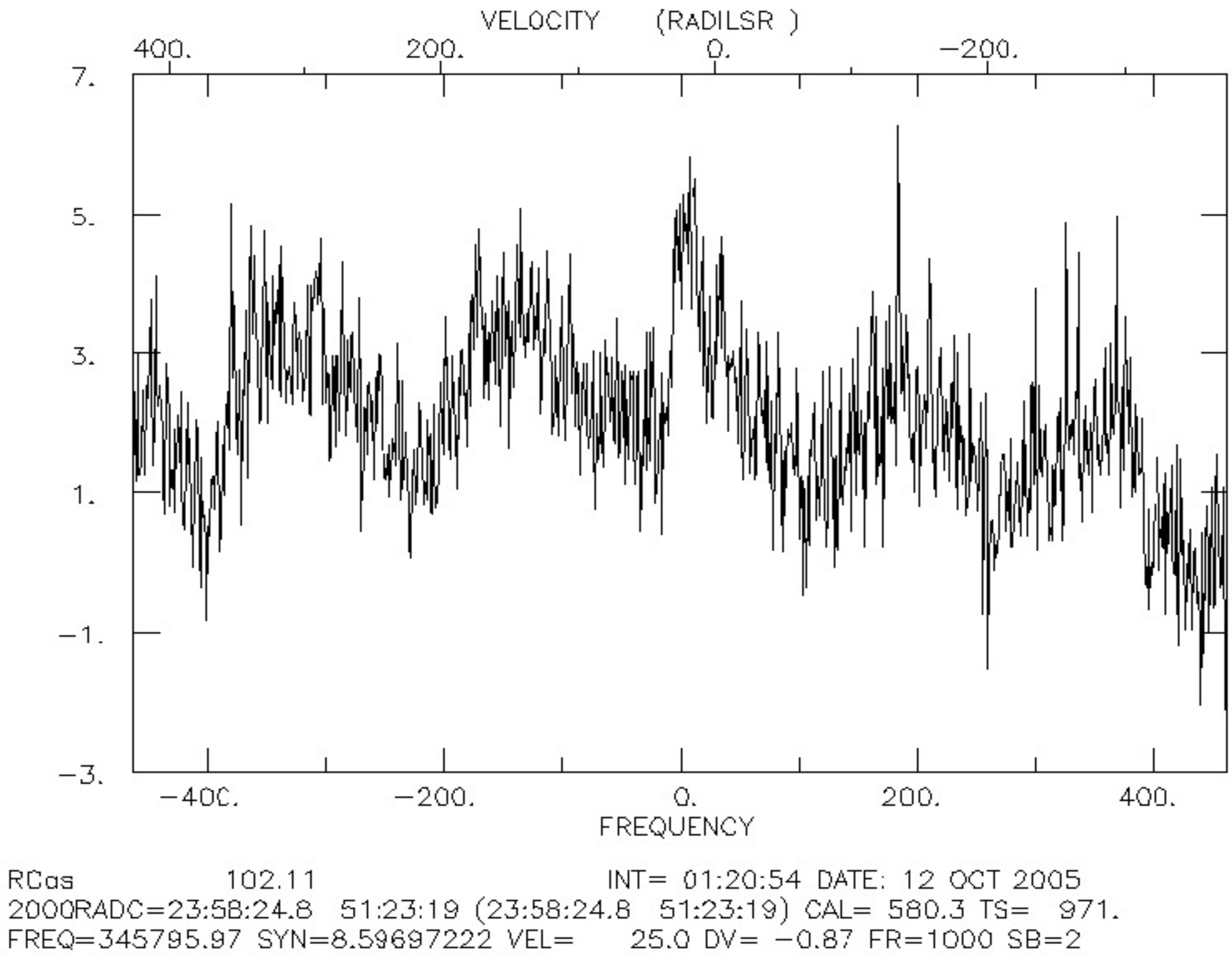
- Start with 1- 8 $M_\odot$ Star
- At end: 0.4 – 0.7 $M_\odot$ in White Dwarf
- <0.1 $M_\odot$ in ionized gas
- Left with 0.2 – 7.2 $M_\odot$



Great Targets for OH, CH, NH, SH, etc.

What is required..

- *No baseline subtraction*
- *No smoothing*
- *No other manipulations*
- *3 - 5 hours Signal - averaging*
- *Position-switching Mode*



The New Technology of ALMA-Type Mixers

- New Type of SIS Mixers developed for ALMA

⇒ ***"Sideband-Separating"***

- Two mixers with RF and IF Quadrature Hybrids

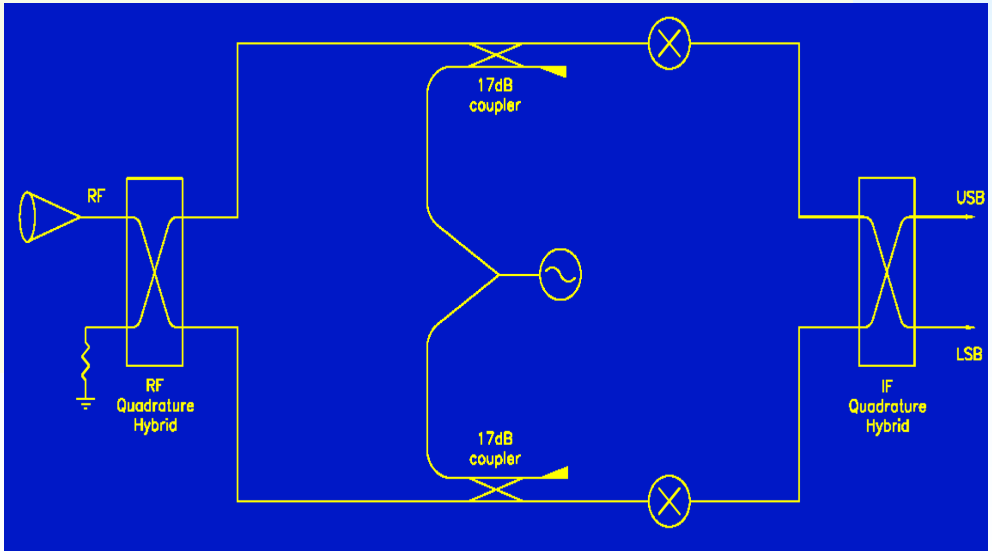
⇒ ***obtain upper and lower sideband simultaneously but separated with good image rejection and two IF outputs***

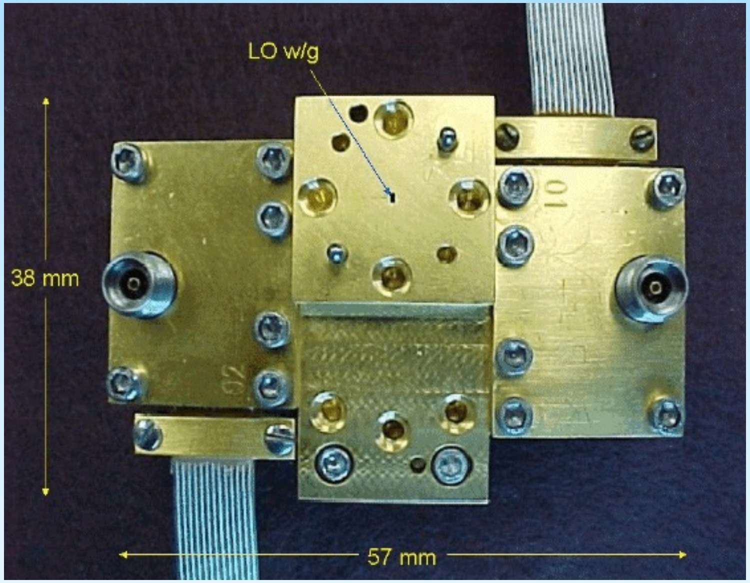
- Split-block design (A. Kerr; NRAO)
- Eliminate ***atmospheric noise*** from image

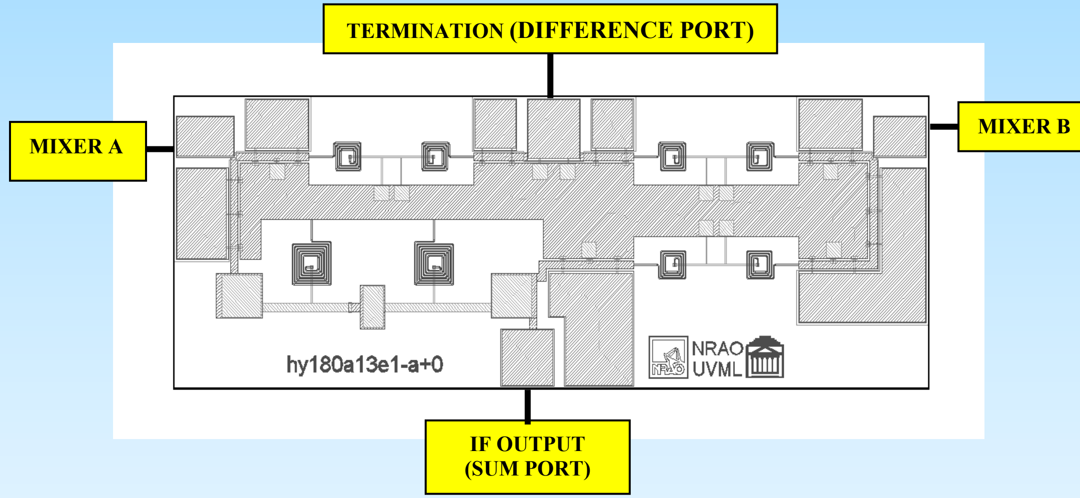
⇒ Most sensitive SIS mixers to date

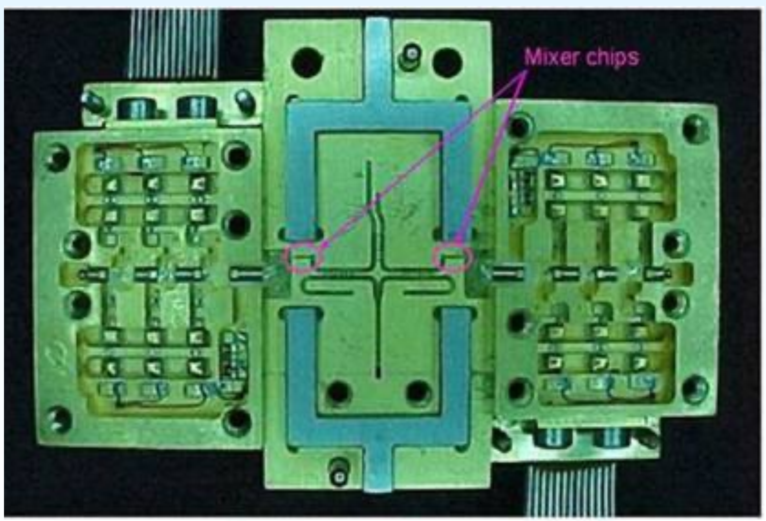
⇒ Unequaled Stability

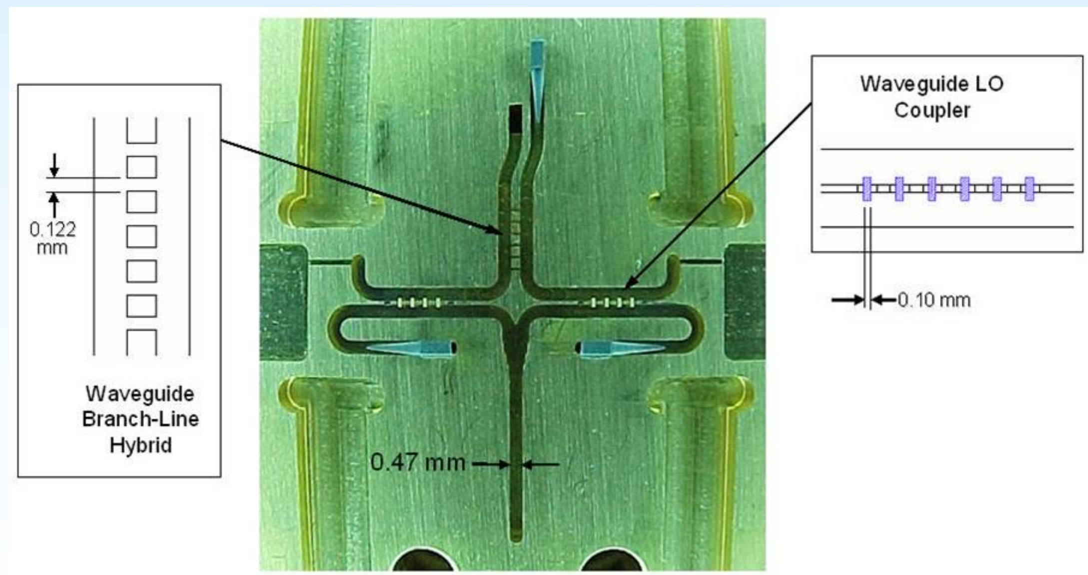
OFFER THE NEXT ORDER of MAGNITUDE GAIN in OBSERVING SENSITIVITY




LO w/g
38 mm
57 mm


TERMINATION (DIFFERENCE PORT)
MIXER A
MIXER B
hy180a13e1-a+0
NRAO
UVML
IF OUTPUT
(SUM PORT)


Mixer chips

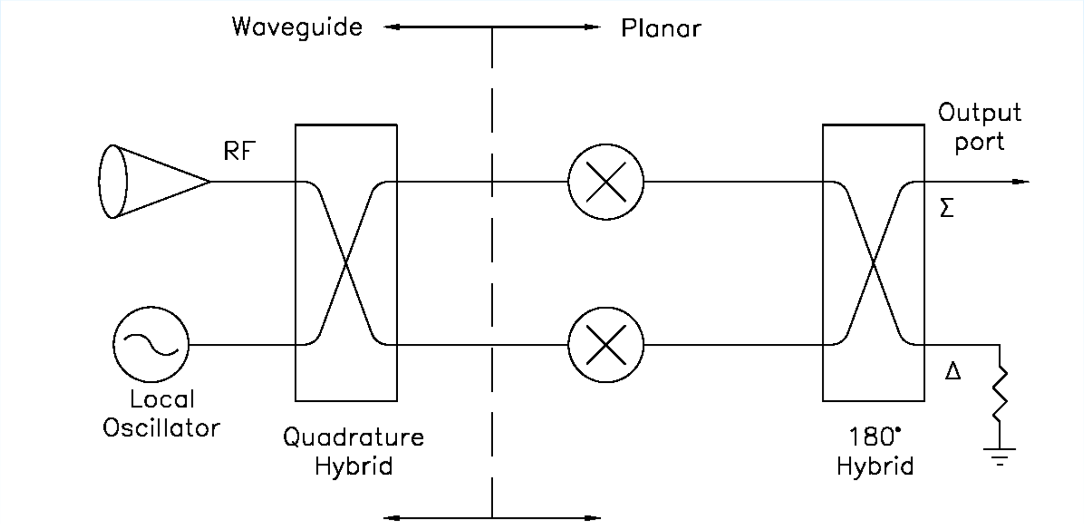

0.122
mm
Waveguide
Branch-Line
Hybrid
0.47 mm
Waveguide LO
Coupler
0.10 mm

Balanced Mixers: A New Development

- "Balanced" mixers an advantage
  - ⇒ Phase balance of RF and LO signals
  - ⇒ eliminates LO noise (5 - 10 K)
  - ⇒ reduces LO power requirement by factor of 50 (THz frequencies)
- Some components already available

(180° hybrid: Nb on quartz substrate)

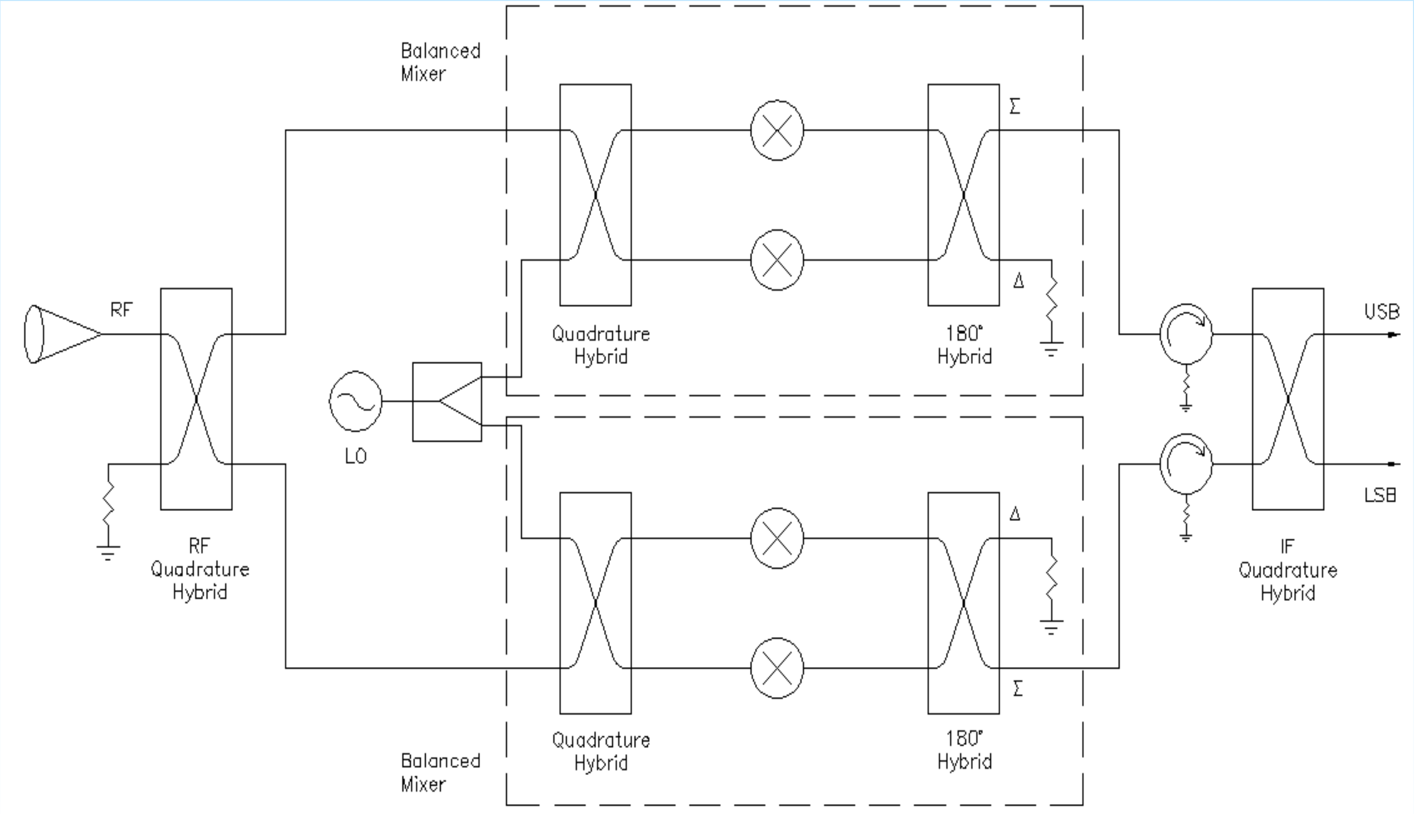
Balanced Mixer design



A.Kerr
NRAO

A Combined SBS/Balance Mixer

Arizona/NRAO collaboration (Band 8: 385 – 500 GHz)



Future Wish Lists

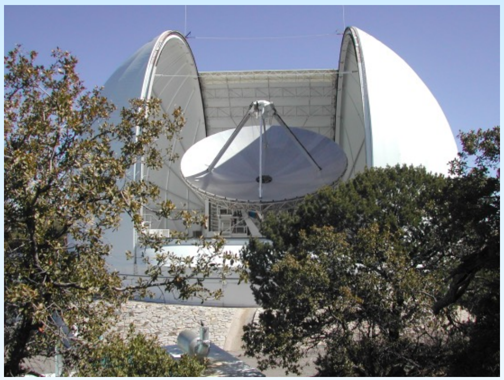
- Sideband-Separating, Balanced Heterodyne Receivers
  ⇒ Capitalize on developments for ALMA
- ALMA Bands 8, 9, 10: currently DSB, but **SBS** work in progress for Band 8, Band 9
- Band 10: A New **NbTiN** material (pure niobium)
- The BEST in
  ⇒ Sensitivity
  ⇒ Stability
- Enable

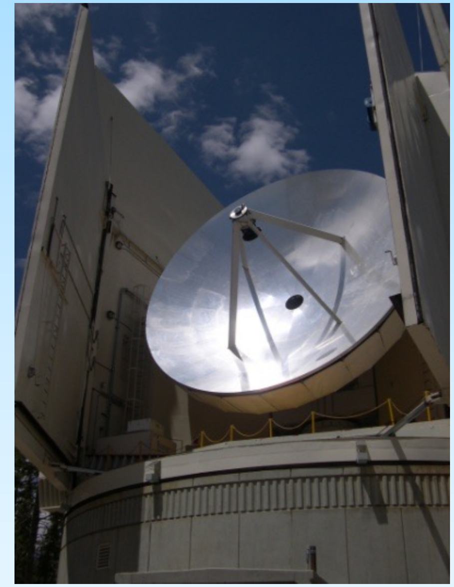
New Spectroscopic Observations With SOFIA

Receiver Bands

Band Number	Frequency Range (GHz)	Wavelength (mm)
1	31.3 - 45.0	6.7 - 9.6
2	67 - 90	3.3 - 4.5
3	84 - 116	2.6 - 3.6
4	125 - 163	1.8 - 2.4
5	163 - 211	1.4 - 1.8
6	211 - 275	1.1 - 1.4
7	275 - 373	0.8 - 1.1
8	385 - 500	0.6 - 0.8
9	602 - 720	0.4 - 0.5
10	787 - 950	0.3 - 0.4

Thank you !





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