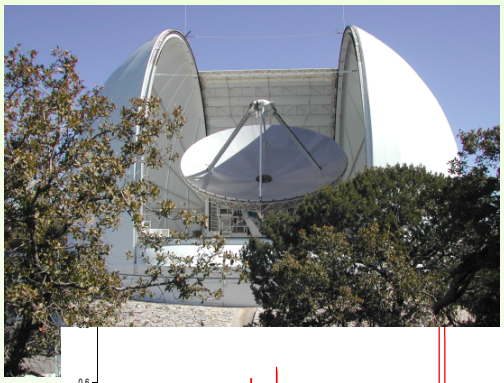
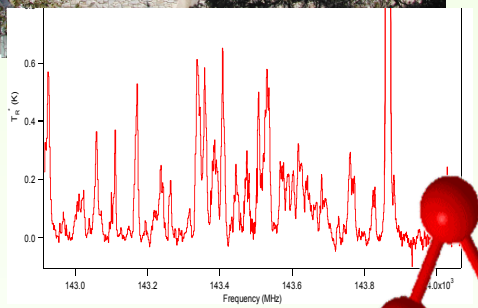
Tracing Molecular Material from Circumstellar Envelopes into the Diffuse ISM





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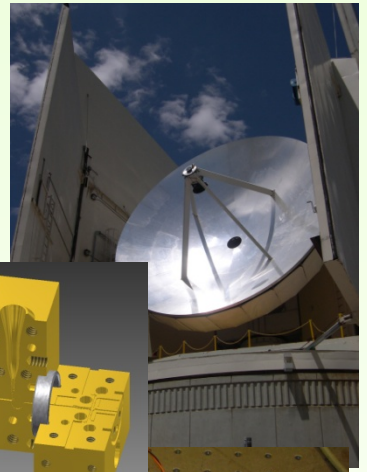
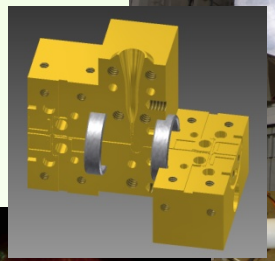
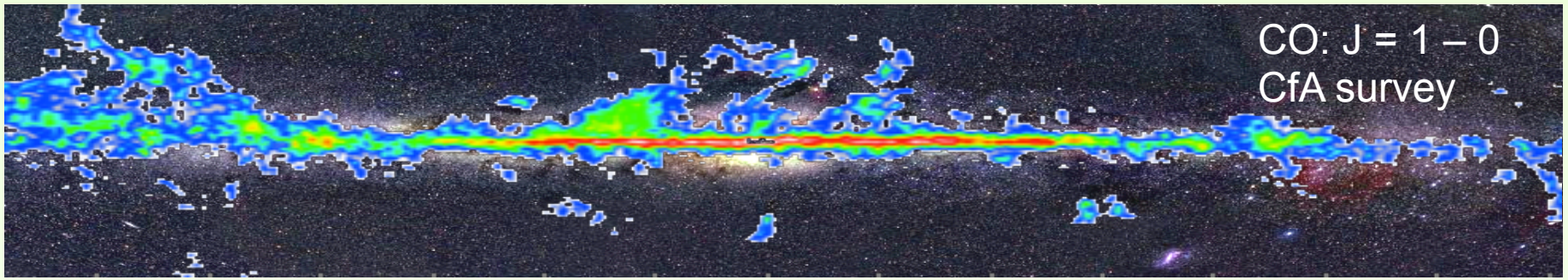




The Success of Molecular Astrophysics

- Molecular Astrophysics: 37 Years of Investigation
  ⇒ Universe in truly ***MOLECULAR*** in nature
- Molecular Gas is Widespread in the Galaxy and in External Galaxies



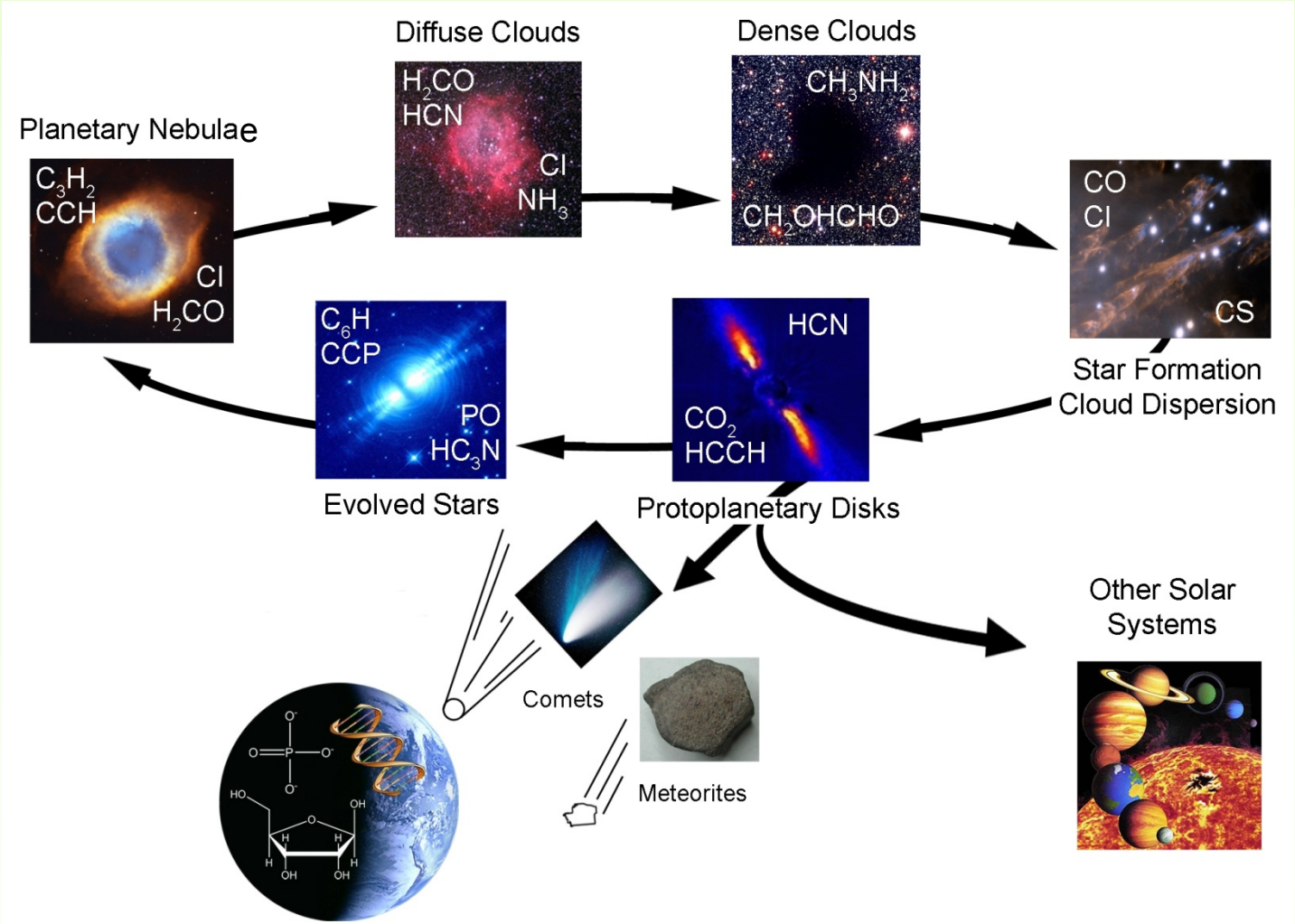
- ***50% of matter*** in inner 10 kpc of Galaxy is MOLECULAR
- Molecular clouds ***largest well-defined objects*** in Galaxy (1 - 10^6 $M_\odot$)
- COLD and DENSE by interstellar standards: T ~ 10 – 100 K; n ~ 10^3 - 10^7 cm^{-3}
- ***Unique tracers*** of chemical/physical conditions in **cold, dense gas**
  ⇒ **New window** on astronomical sources
  ⇒ Critical to understanding of Star and Solar System Formation, Evolved Stars, Galactic Structure, ISM in External Galaxies, etc.

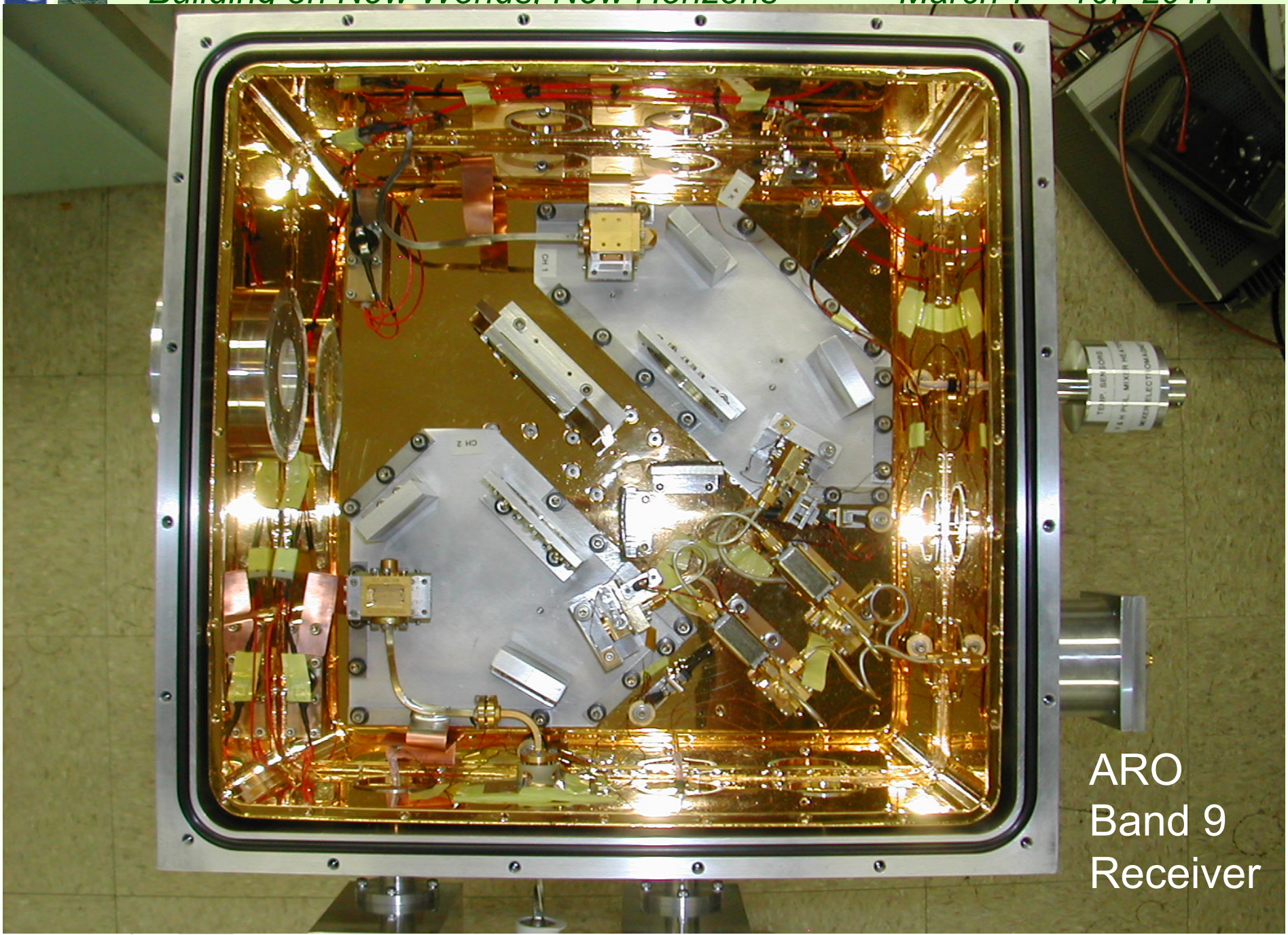
But is there more to this Story ??

- **Elements and Molecules**

⇒ originate in *dying stars*

- **Molecular material** *cycled through other phases* before reaching dense clouds, protostellar disks
- *Are these phases linked ?*





ARO
Band 9
Receiver

Circumstellar Origins

- Stars with ~ 1 - 8 $M_\odot$: Most stars

⇒ Follow **common** evolutionary sequence: GIANT BRANCHES

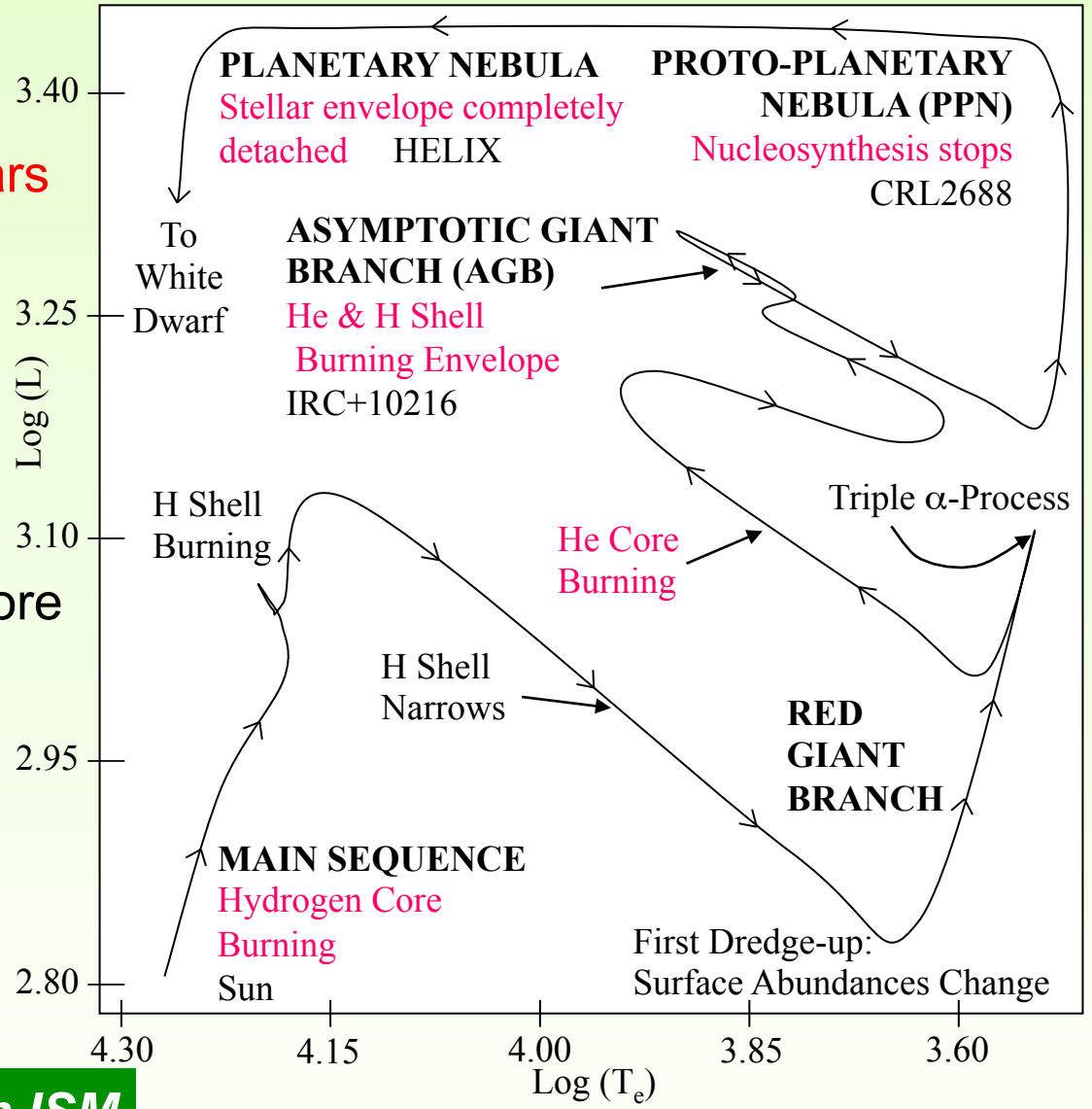
- Deplete hydrogen in core
- Burn H in a shell around core

⇒ Enter **Red Giant Branch**

- Burn, then deplete Helium in core
- Burn He and H in shells

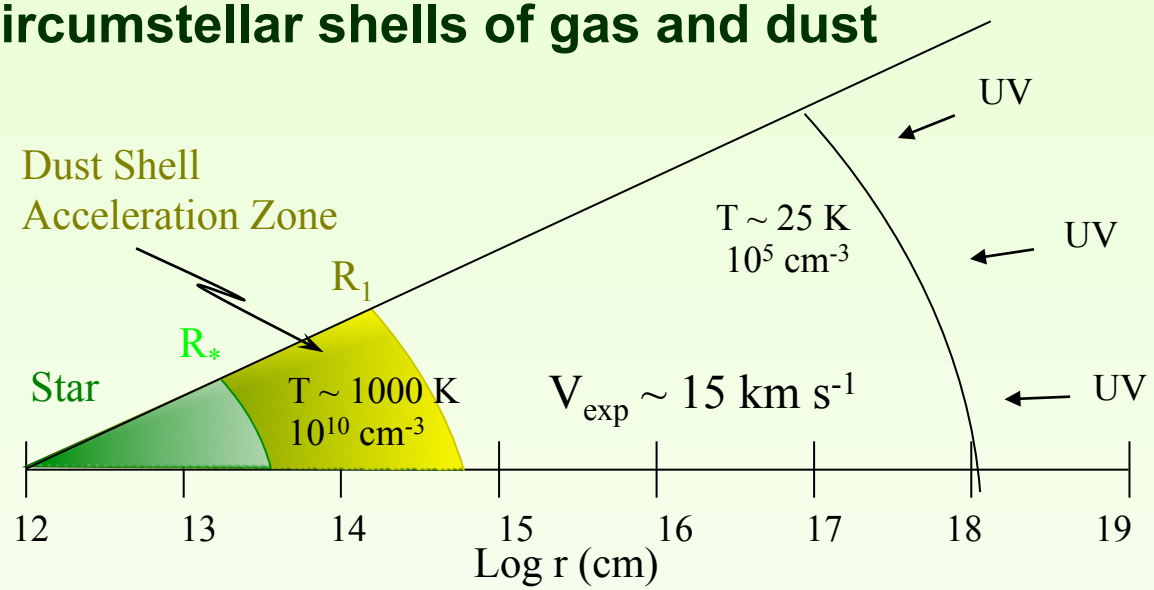
⇒ **Asymptotic Giant Branch** (AGB)

- Significant **Mass Loss** occurs on Giant Branches (~ 0.5 $M_\odot$ remains for star)



⇒ *Supplies 80% of material in ISM*

- Mass loss creates ***Circumstellar Envelope***
- Most Stars: **O > C** (Red giants, supergiants, some AGB)
- Dredge-up events on AGB can create **"carbon stars"** with **C > O**
- **Both O-rich and C-rich circumstellar shells of gas and dust**



- Large T and n Gradients in stellar envelopes
- LTE chemistry near stellar photosphere (T ~ 1000 K)
- UV induced photochemistry at outer shell edges
- C - Rich Envelopes have ***UNIQUE Carbon-Based Chemistry***

Based on studies of one object: ***IRC+10216***

MOLECULAR INVENTORY of **C-RICH** CIRCUMSTELLAR SHELLS

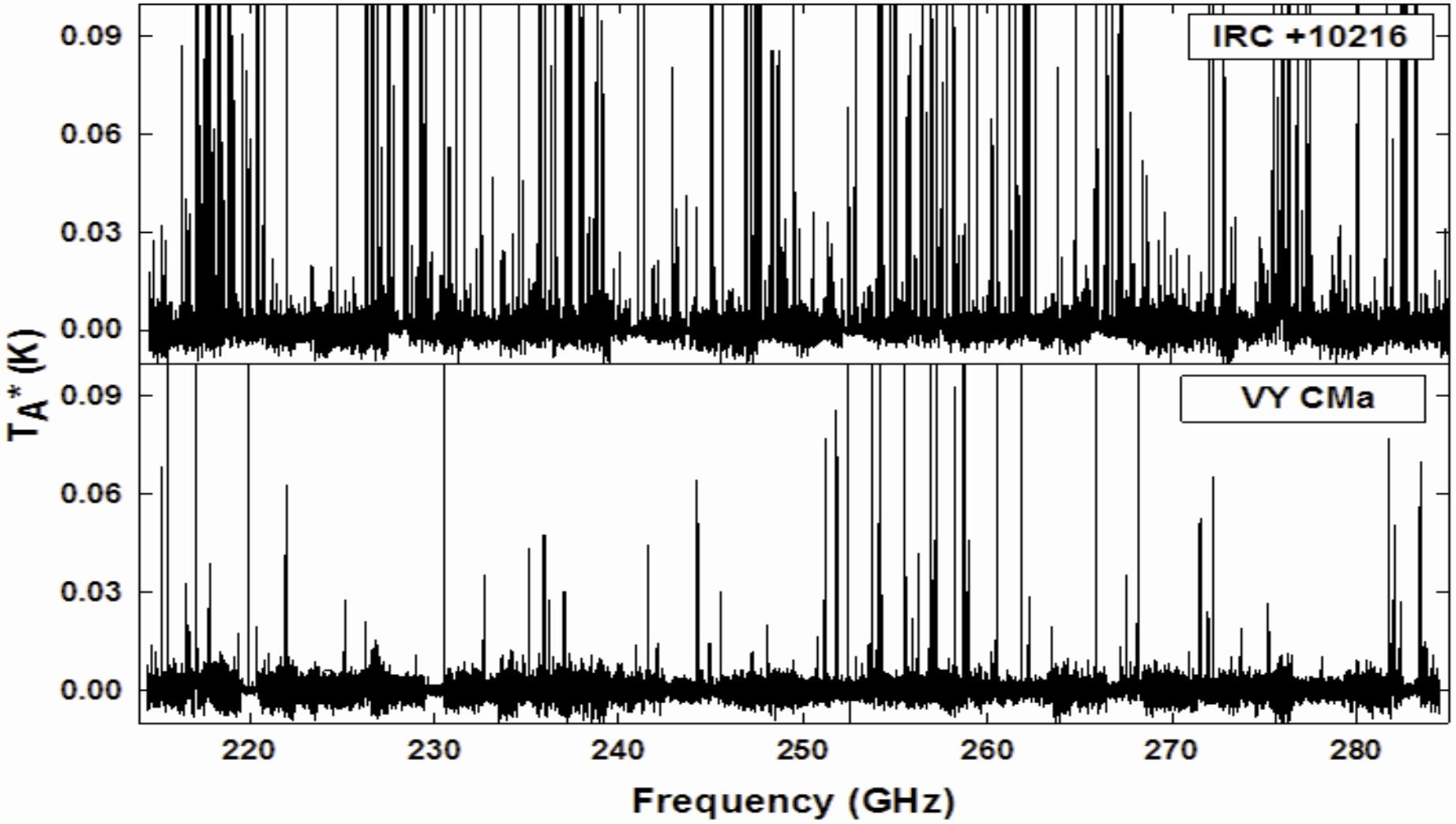
CO	CCH	HC_3N	CCS	SiCN	MgNC
CS	C_3H	HC_5N	C_3S	SiC	MgCN
CN	C_3O	HC_7N	C_3N	SiC_2	AlNC
HCN	C_4H	HC_9N	C_5N	SiC_3	KCN
HCCH	C_5H	CH_2CN	HC_4N	SiC_4	NaCN
HNC	C_6H	H_2C_4	c-C_3H_2	H_2CS	CP
H_2CCH_2	C_7H	H_2C_6	CH_3CN	C_4H^-	CCP
CH_4	C_8H	C_2	HC_2N	C_6H^-	HCP
H_2CO	c-C_3H	C_3	HCCNC	C_8H^-	PN
CH_3CCH	CH_2CHCN	C_5		C_5N^-	PH_3

57 C-Bearing Molecules

(5 with phosphorus)

SiH_4	SiO	KCl	NaCl	NH_3
SiN	SiS	AlF	AlCl	H_2S

And What About Oxygen-Rich Circumstellar Gas ?

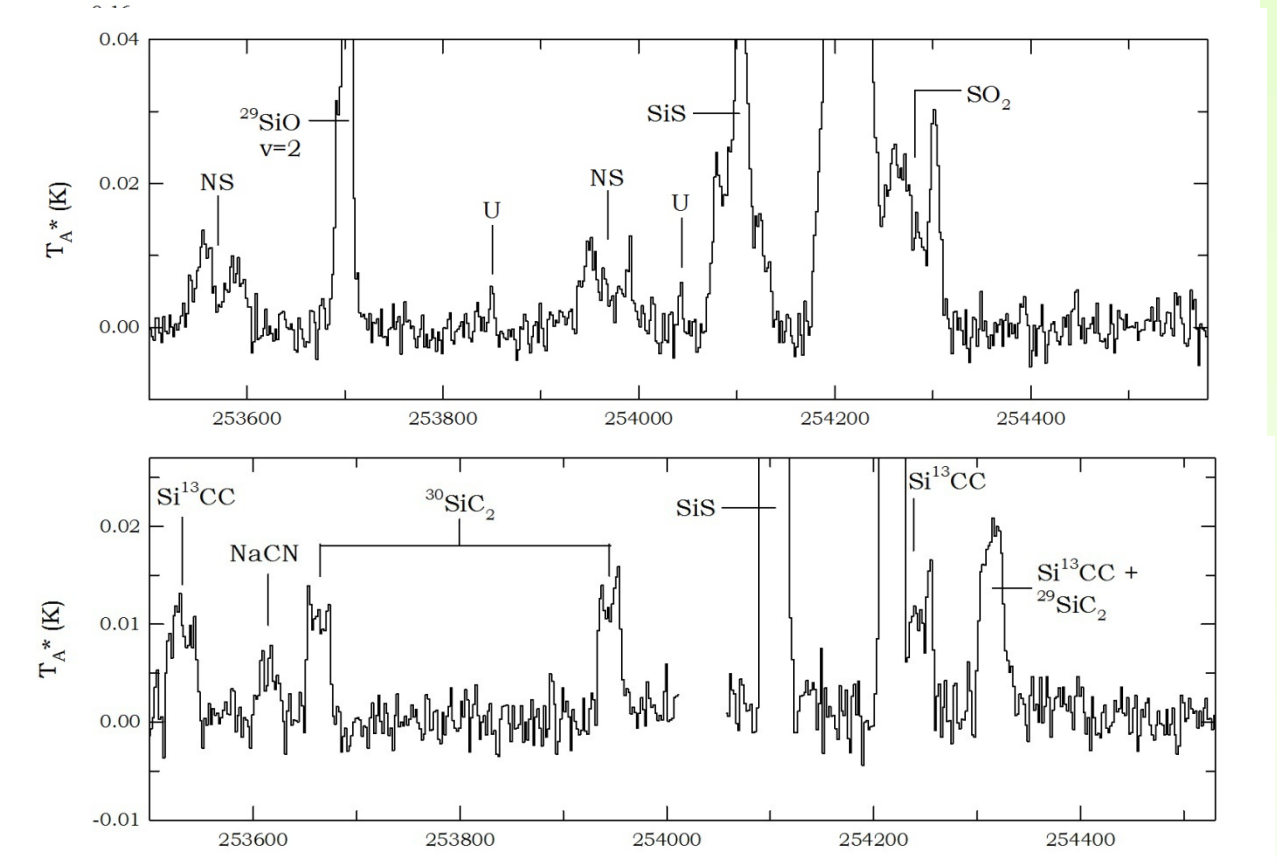


Most sensitive survey to date: noise level ~ 5 mK

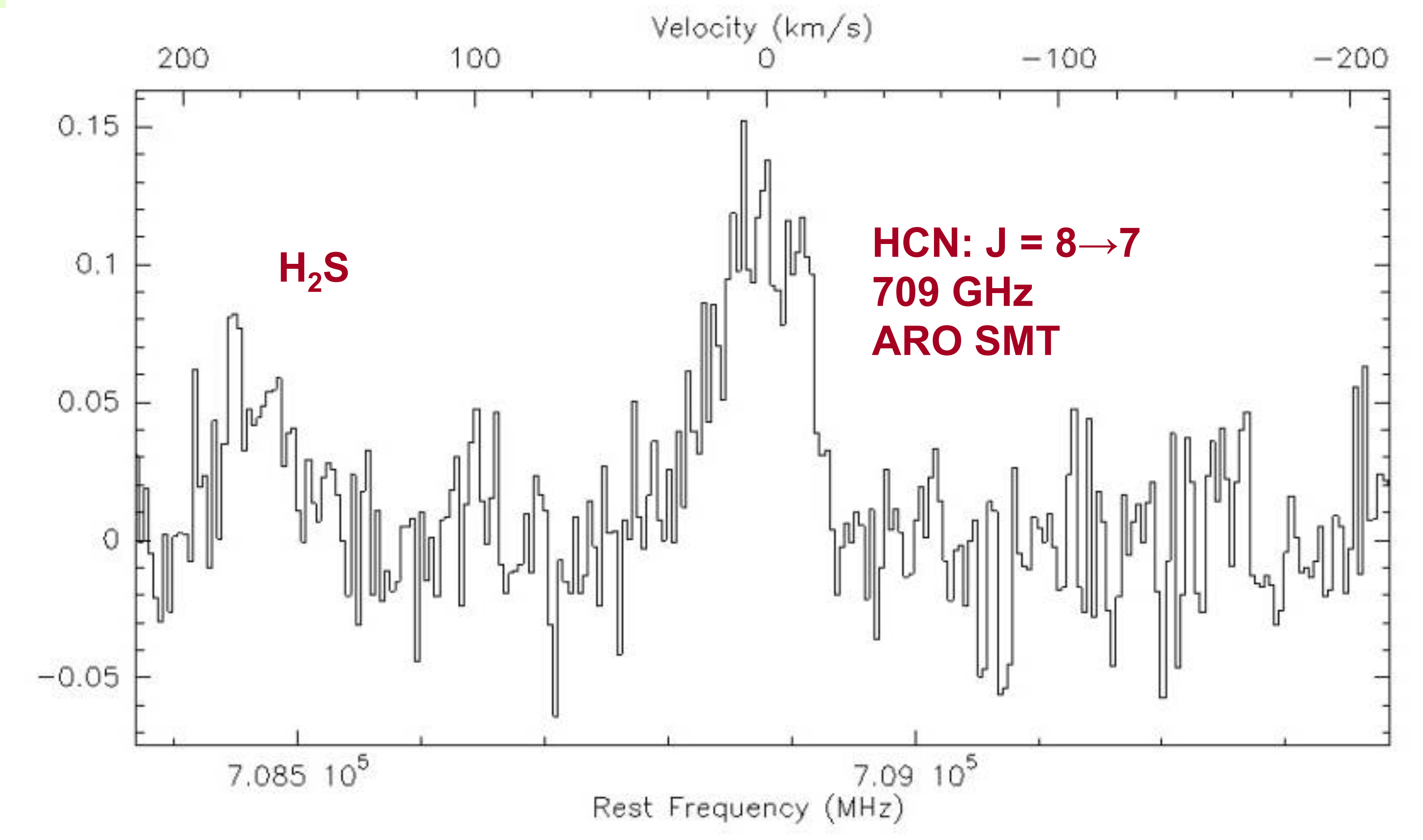
Survey Results

- **IRC+10216:**
  - 720 lines total
  - 124 unidentified
- **VY Canis Majoris:**
  - 131 lines total
  - 14 unidentified

OH	NH_3	NO
CO	H_2S	SiS
CN	SO_2	SiO
CS	SO	PN
HCN	H_2O	NaCl
HNC	PO	NS
HCO^+	AlO	AlOH



- **C_4H, SiC_2 and NaCN** dominate IRC+10216 spectrum
- VY CMa spectrum dominated by **SO_2, SiO, SiS**
- **VY CMa** surprises: **New molecules** & **unusual line shapes**



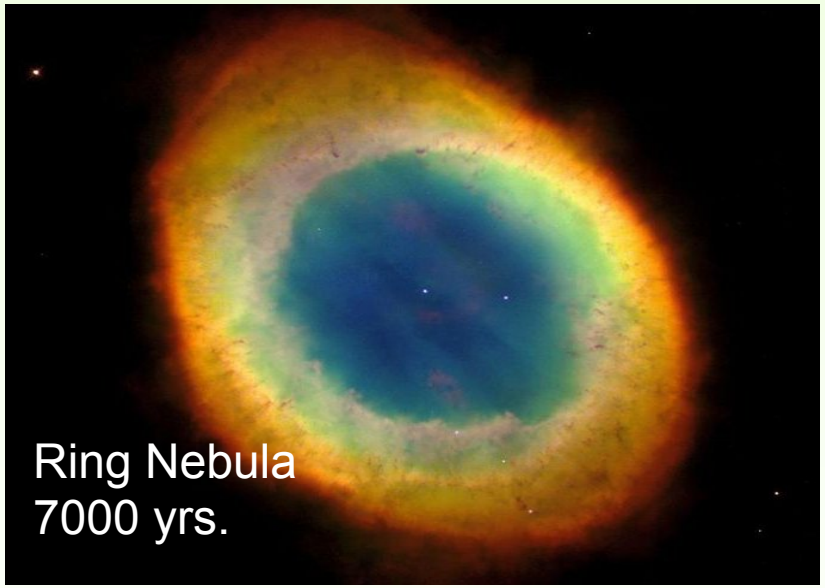
Velocity components trace different episodes of mass loss

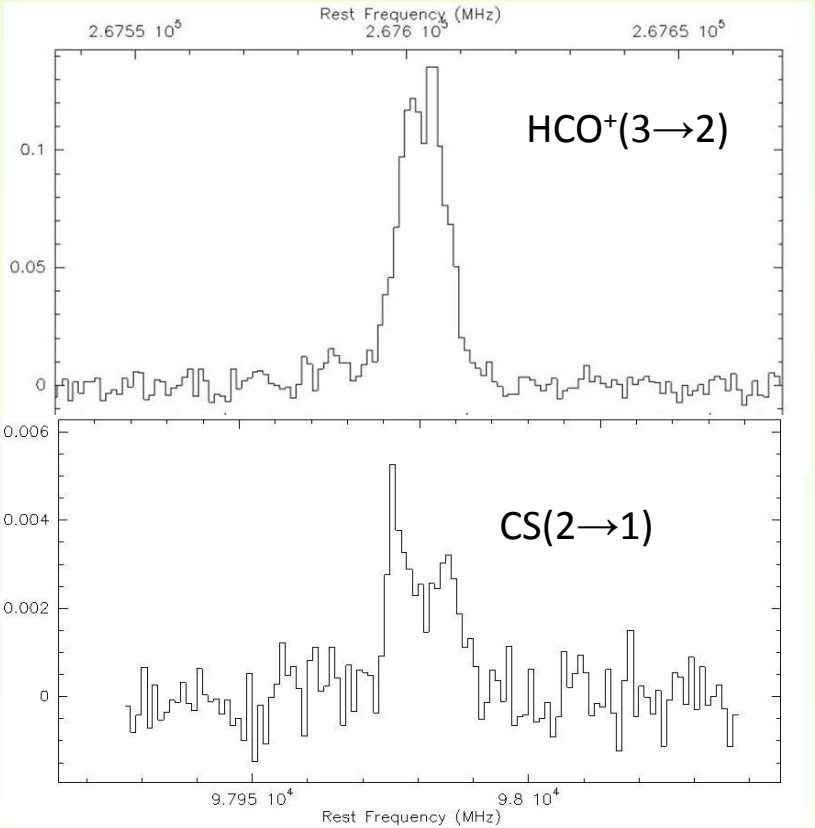
NML Cygnus: 1mm survey at SMT (Dodd et al.)

From Circumstellar Shells to 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 ?

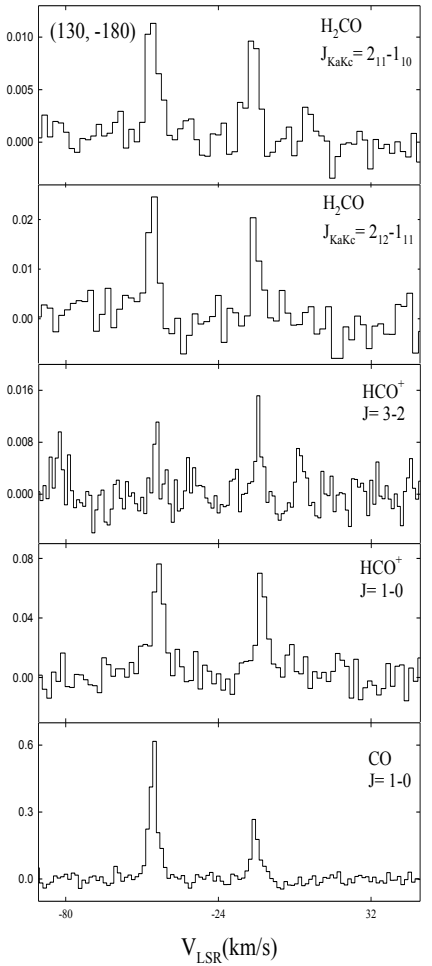
⇒Survey of Middle-Aged to Old PNe
(Dumbbell, M2-48, K4-47, Ring, etc.)

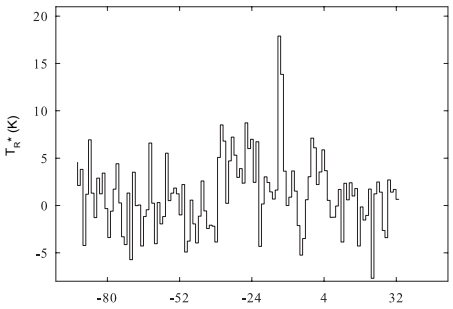


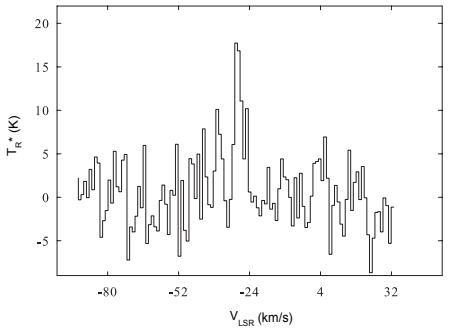


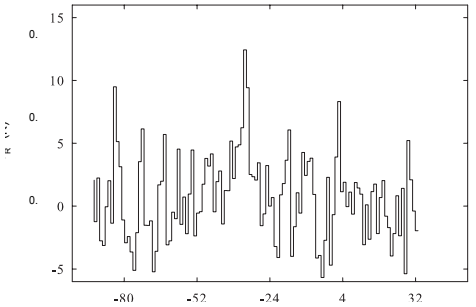
The Helix Nebula at 12,000 yrs.

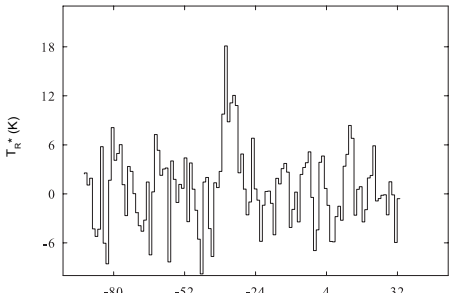
H_2CO ($2_{12} \rightarrow 1_{11}$)

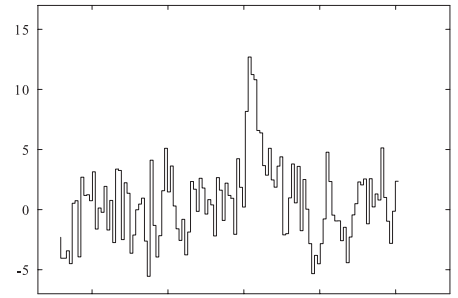


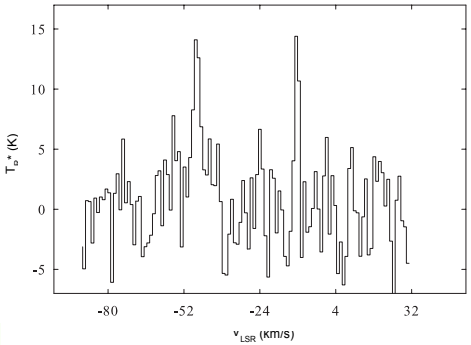


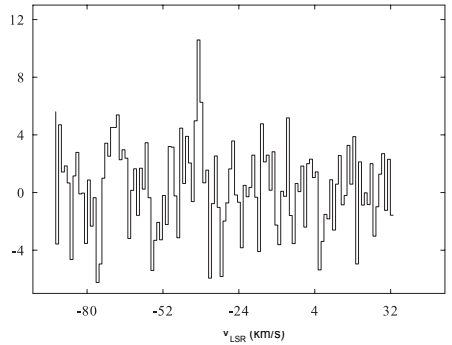


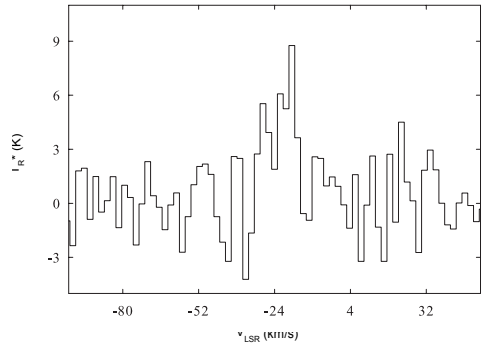












Zack & Ziurys 2011

Velocity components traced in CO, HCO^+, H_2CO

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

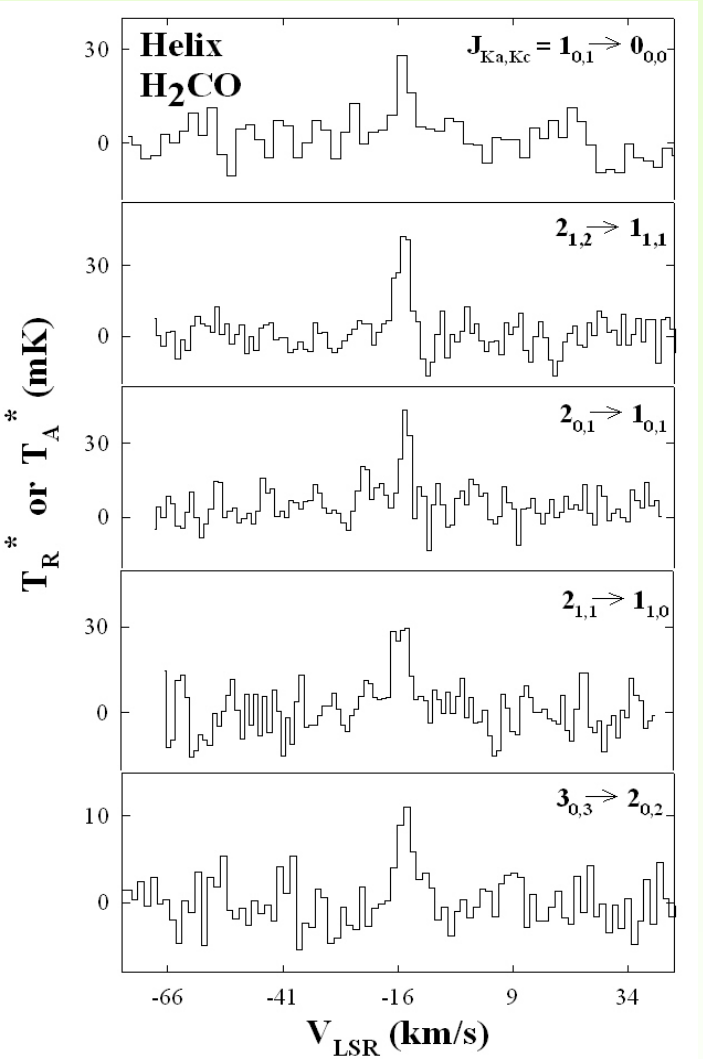
⇒ Observed with ARO 12 m (Tenenbaum et al. 2009)

- 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 $M_\odot$

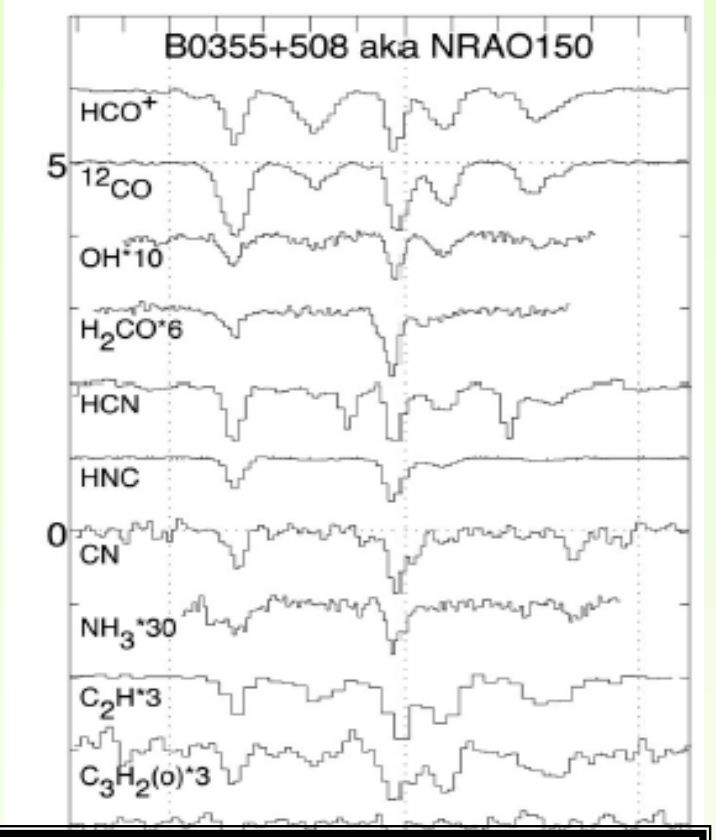


PNe Ejecta Into Diffuse Clouds

- Planetary Nebulae **disperse into diffuse ISM**
- Fate of the surviving molecular gas ?
- *Observations towards Diffuse Clouds*

(Liszt and Lucas; Liszt et al; Maier et al)

Molecule	Helix Nebula	Diffuse Clouds[a)]
H_2CO	1 x10^{-7}	4 x 10^{-9}
C_2H	1 x10^{-6}	3 x10^{-8}
c-C_3H_2	1 x 10^{-8}	1 x10^{-9}
CO	9 x 10^{-4}	3 x10^{-6}



- Diffuse Clouds and Planetary Nebulae similar set of molecules
- Molecules cannot be accounted for by in-situ gas-phase formation (Snow & McCall 2006)

⇒ ***Remnant molecules*** from planetary nebulae

⇒ Origin of Diffuse Interstellar Bands ??

Contribution of Laboratory Spectroscopy

- And what about the U-lines ?
- How are molecular lines assigned in first place ?

⇒ Contribution of ***Laboratory Astrophysics***

⇒ High-resolution gas-phase spectroscopy

- Different techniques

 ⇒ mm/submm direct absorption

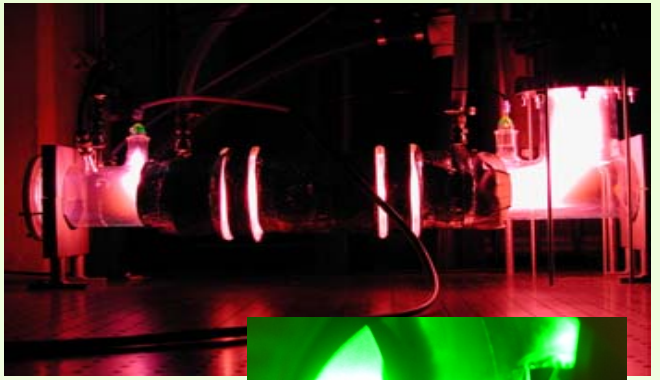
 ⇒ velocity modulation (selective detection of ions)

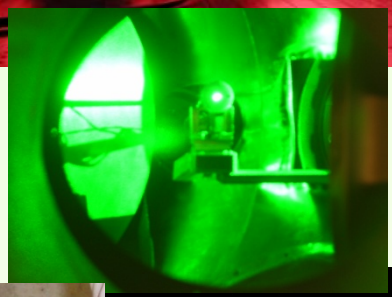
 ⇒ Fourier transform microwave (FTMW) spectroscopy

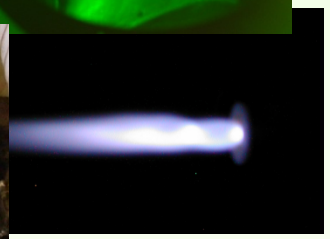
- NOT commercially available
- ***Synthesizing the molecules***

 ⇒ DC/AC discharge, laser ablation, supersonic jet nozzle, Broida-type oven

- Often crash-and-burn chemistry

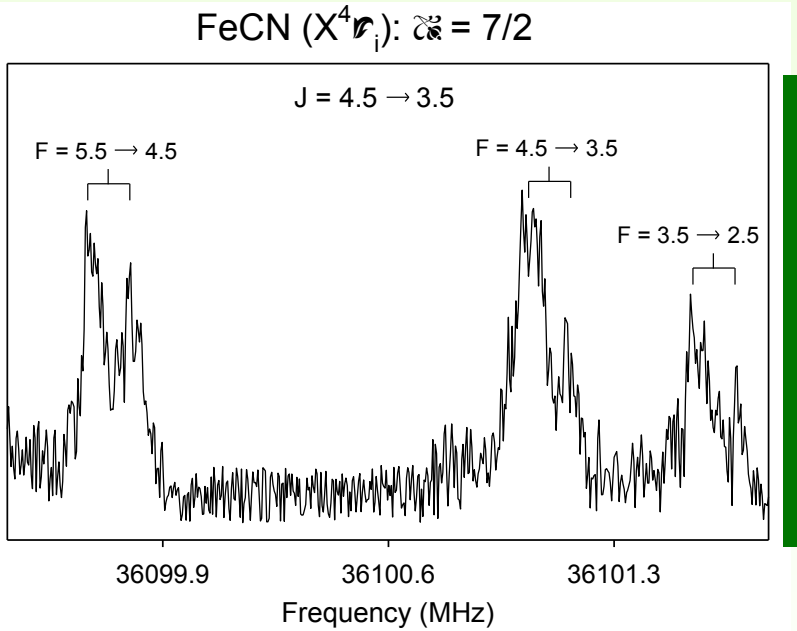




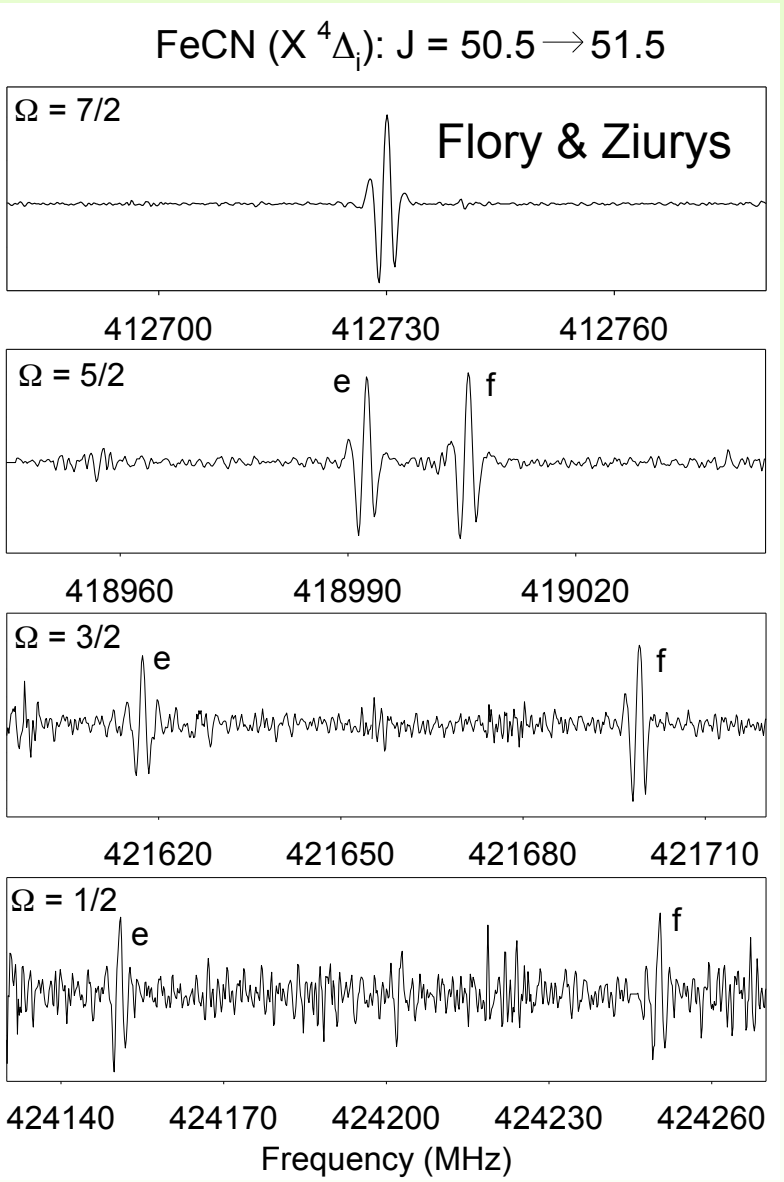


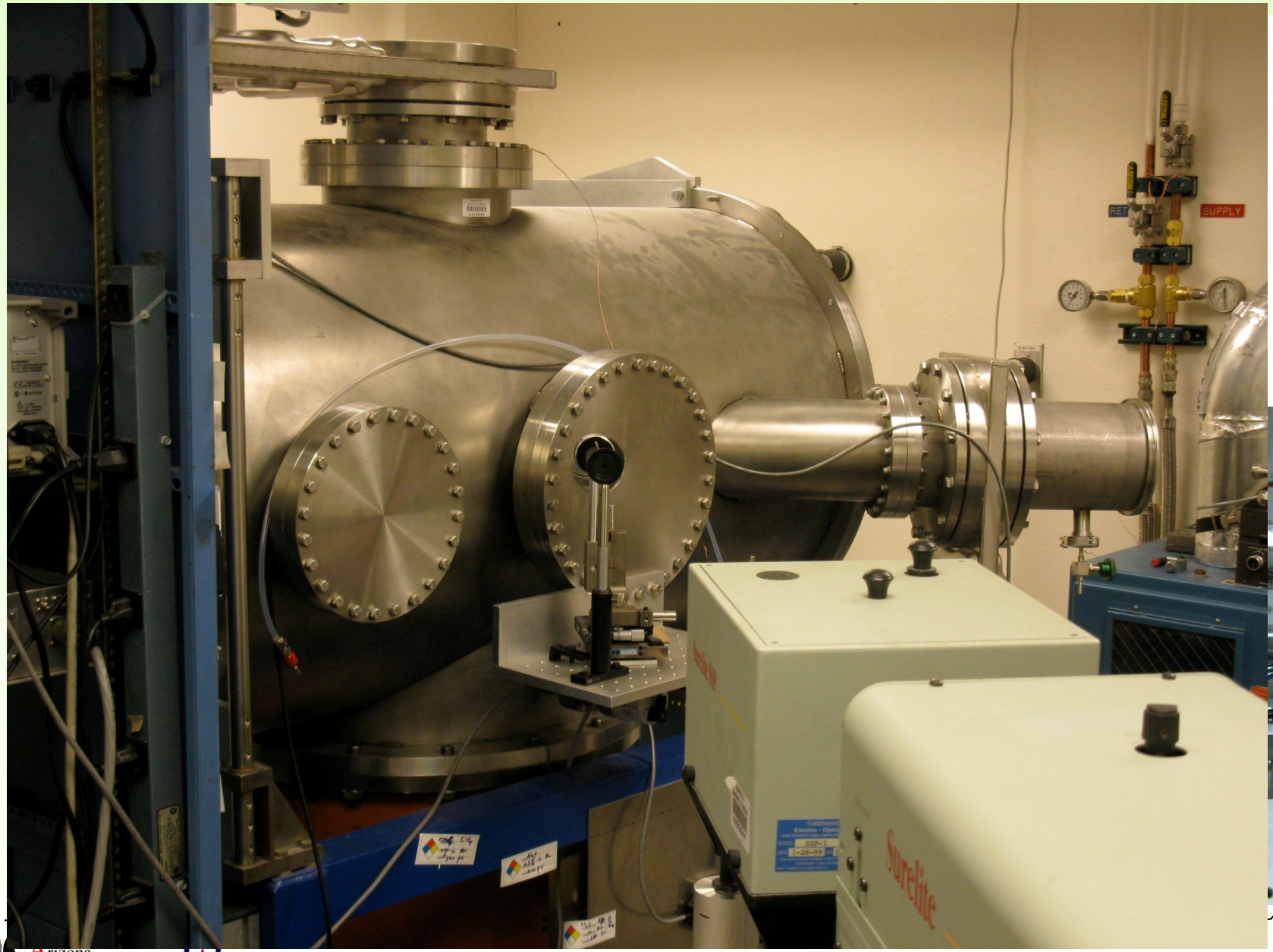
FeCN: A Case Study

- Metal cyanides abundant in IRC+10216
- **FeCN** a likely species
- 10 years of laboratory effort...$Fe(CO)_5$
- Spectra suggested **$^4\Delta_i$ ground state**
- Theory predicted $^6\Delta_i$ ground electronic state
- FTMW spectrum proved this beyond doubt



New Molecule Source: Laser Ablation/ DC discharge

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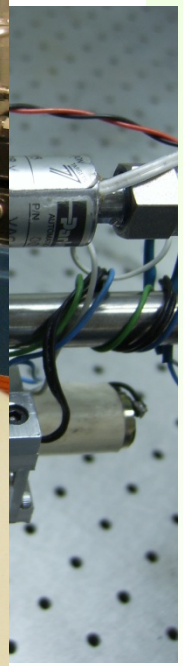

Lucy, DeWayne, and Ming

Conclusions

- Molecular observations of Oxygen-rich Circumstellar Envelopes
  ⇒ Interesting Chemistry and Kinematics (Hypergiants)
- C and O-rich envelopes have many Identified (AND UNIDENTIFIED) Lines
- Planetary nebulae: contain **molecular** material
- **MOLECULAR MATERIAL IS PASSED ON FROM REGION TO REGION**
- Not necessarily returned to Atomic State
- Interstellar Chemistry is remarkably ROBUST
- Massive, Molecular (often C-rich) Environment of Stellar Ejecta

⇒ Passed on to diffuse gas

- Dense clouds form from diffuse material
- On to planets via comets, meteorites, IDP's
- Origin of Organic Chemistry: ***traced to C-rich circumstellar shells***
- ***ALL MADE POSSIBLE: LAB ASTROPHYSICS***

Arizona Radio Observatory

NSF and NASA
For funding