Diagnostics of Molecular Shocks: From YSOs to SNe

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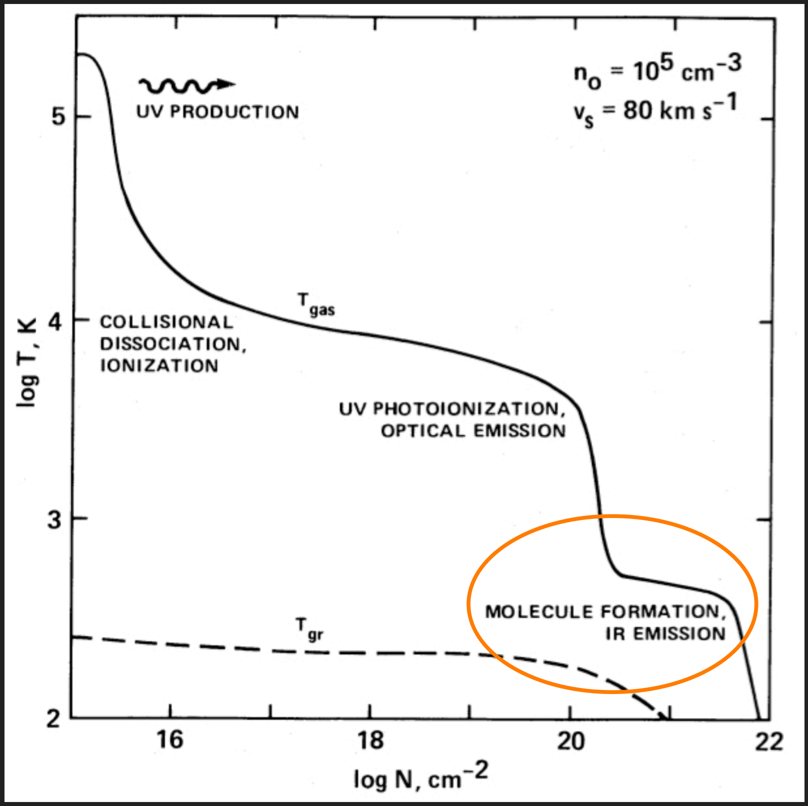
Outline

- Refresher on inputs and outputs
- Observations of shocks in a SNR
- Observations of shocks in star forming regions
- Detection of O_2 …….from shocks?
- Going forward

Shocks: What Good Are They?

- Chemical laboratories: test predictions, especially endothermic reactions and those with barriers
- Allow direct measurements of abundances: e.g. warm CO vs. warm H_2
- Intense line emission (incl. dynamical info)
- Generally large line/continuum

J-Shock Physics



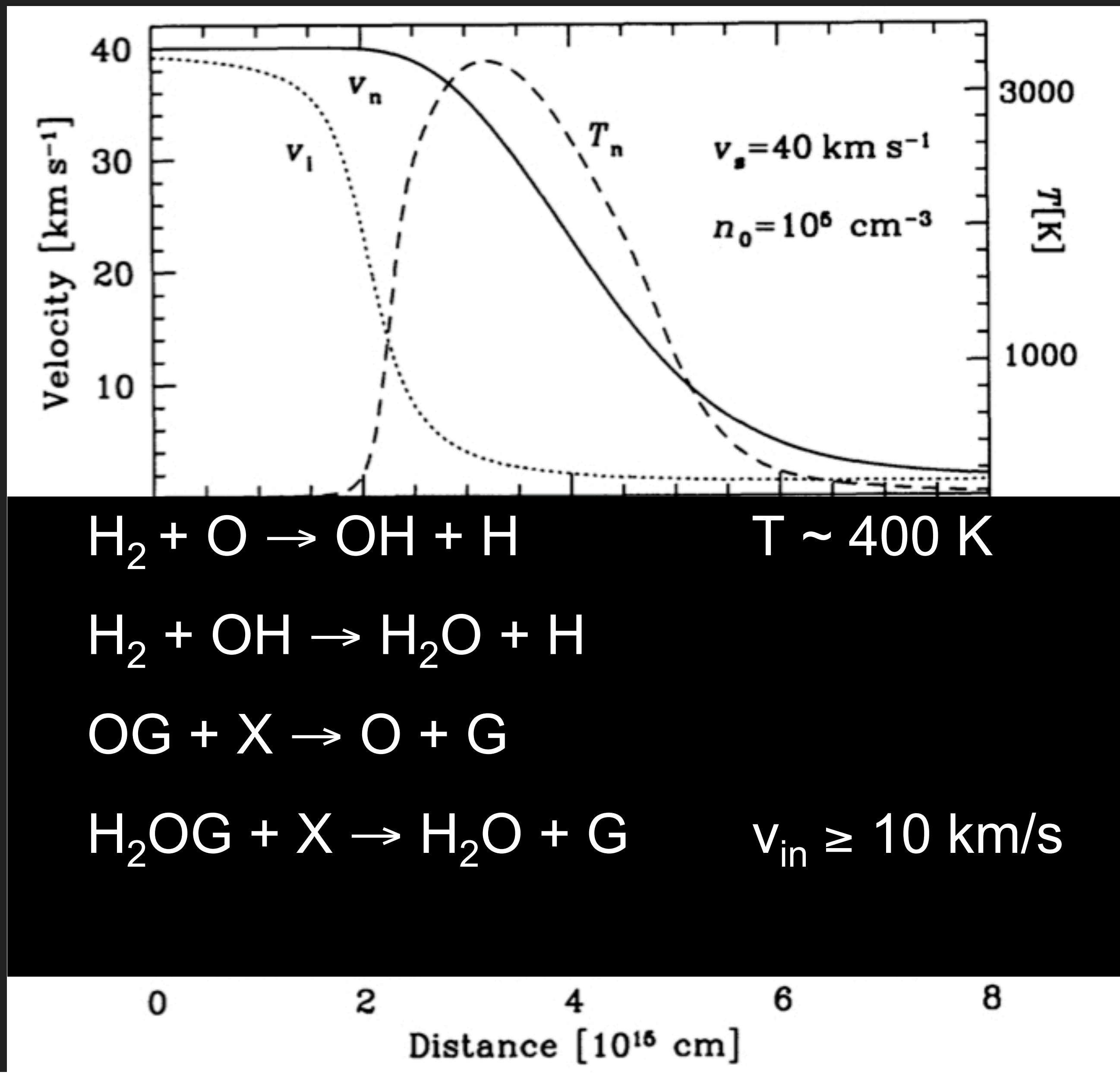
Hollenbach & McKee 1989

- Post-shock: $T>10^4$ K
- Collisional dissociation of H_2
- UV continuum emission
- T ~ 500 K plateau from H_2 formation heating
- H_2 pure rotational: thermal
- H_2 vibrational: formation pumped, "weak"
- IR emission from OI, ionized gas (e.g. FeII, SiII), molecules

C-Shock Physics

- Low ionization fraction: ions and neutrals behave as *weakly-interacting* fluids
- $v_{Ai} > v_{bulk\ motion}$: subsonic in the ions
- $v_{An} < v_{bulk\ motion}$: supersonic in the neutrals
- Ions never shock, so they can *drag* neutrals through what would normally be a discontinuity
- As long as neutral gas can cool efficiently, these conditions are maintained and “shock” is *continuous*
- *Molecular gas stays molecular up to 4000 K!*

C-Shock Profile



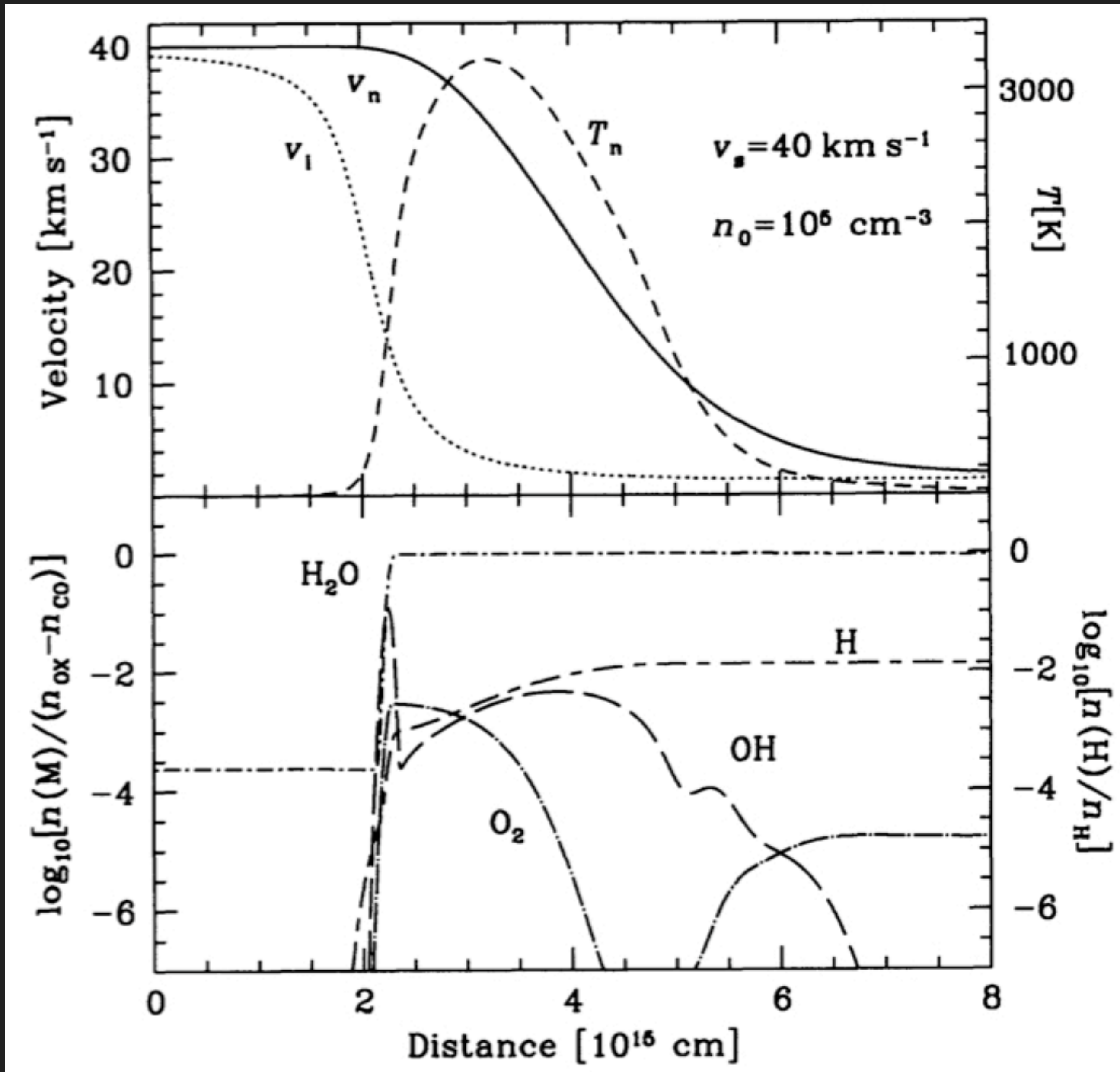
H_2 + O → OH + H   T ~ 400 K

H_2 + OH → H_2O + H

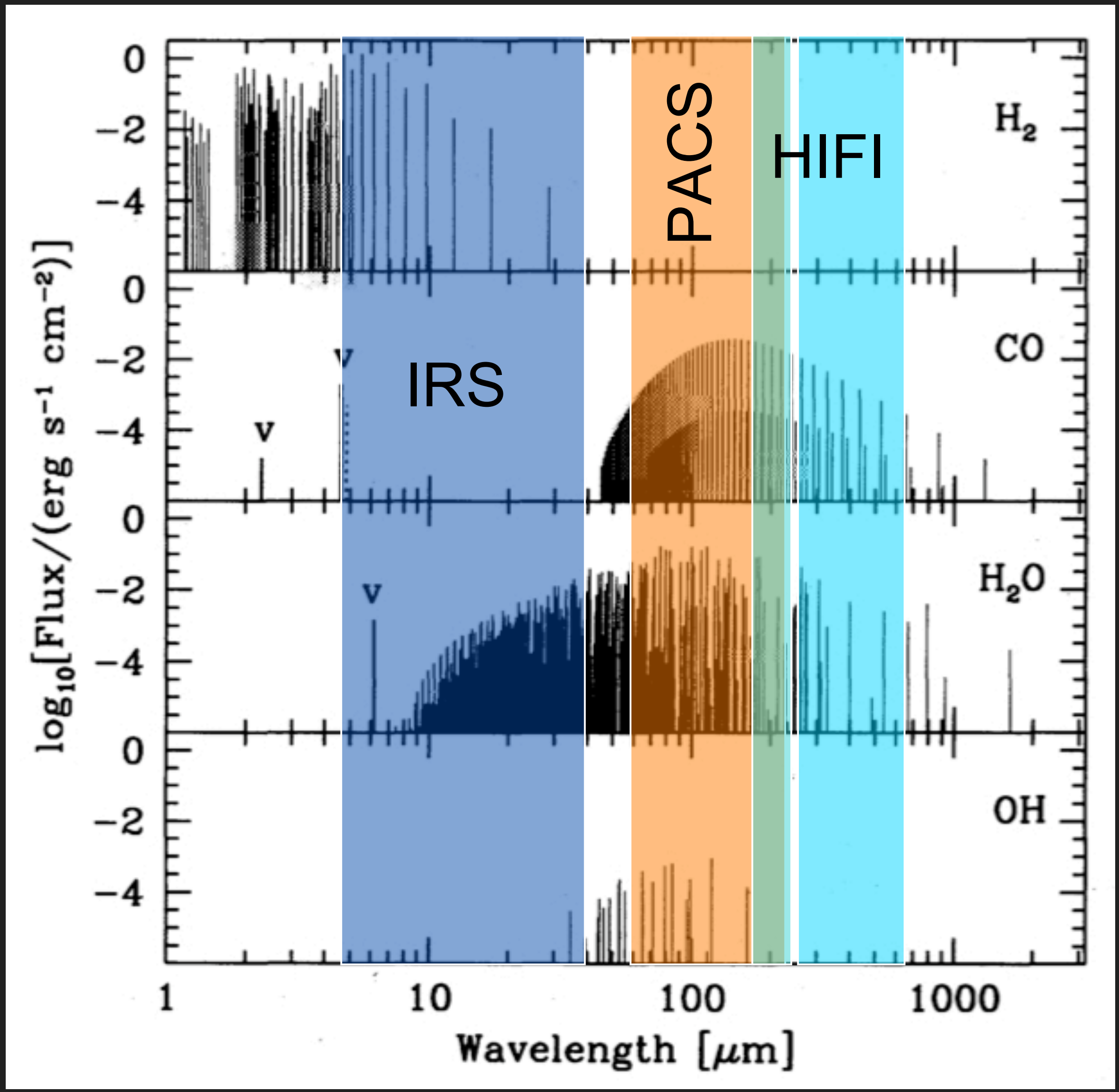
OG + X → O + G

H_2OG + X → H_2O + G $v_{in} \geq 10$ km/s

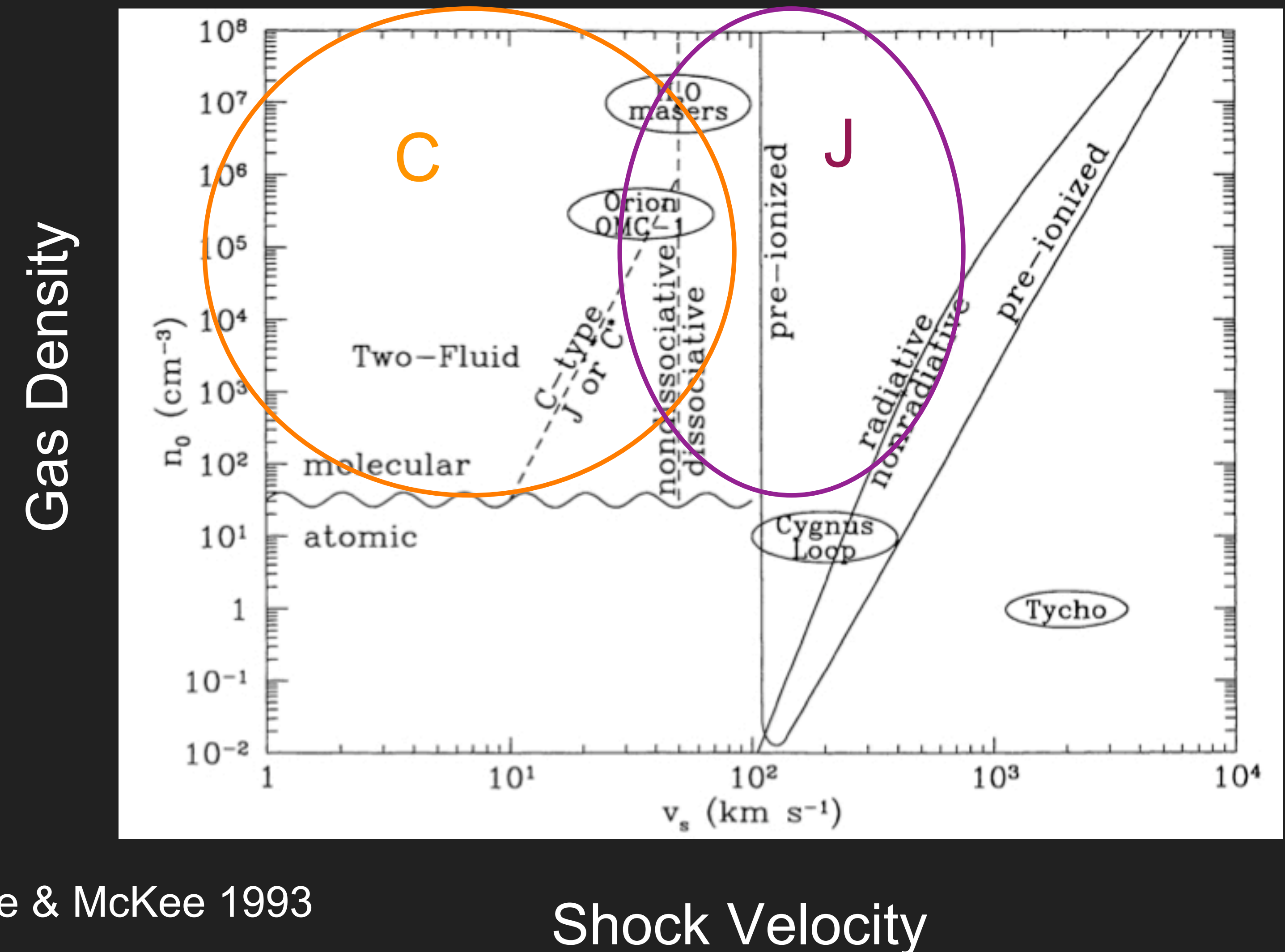
C-Shock Profile



C-Shock Emission Lines

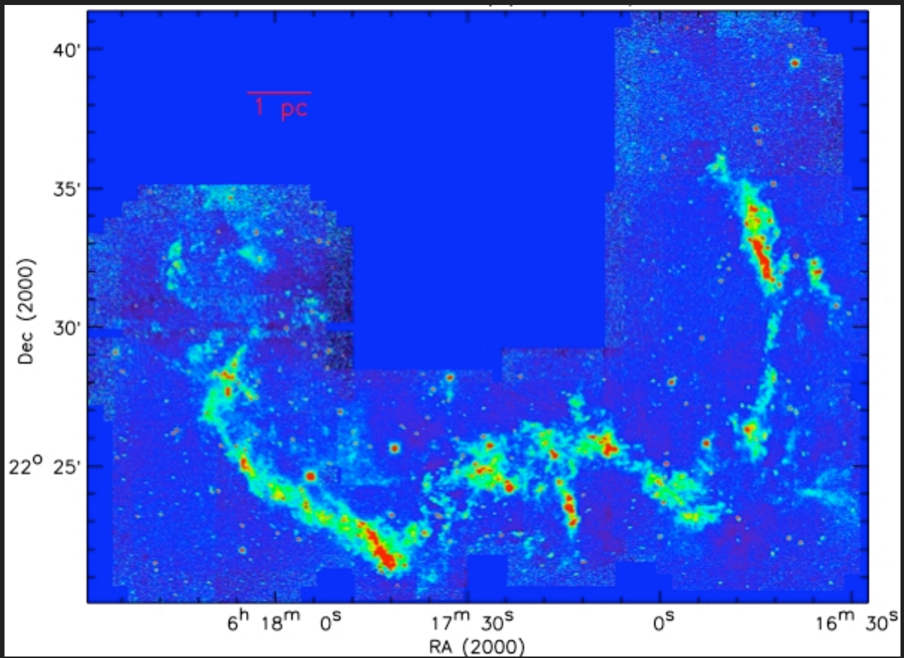


Parameter Space



Draine & McKee 1993

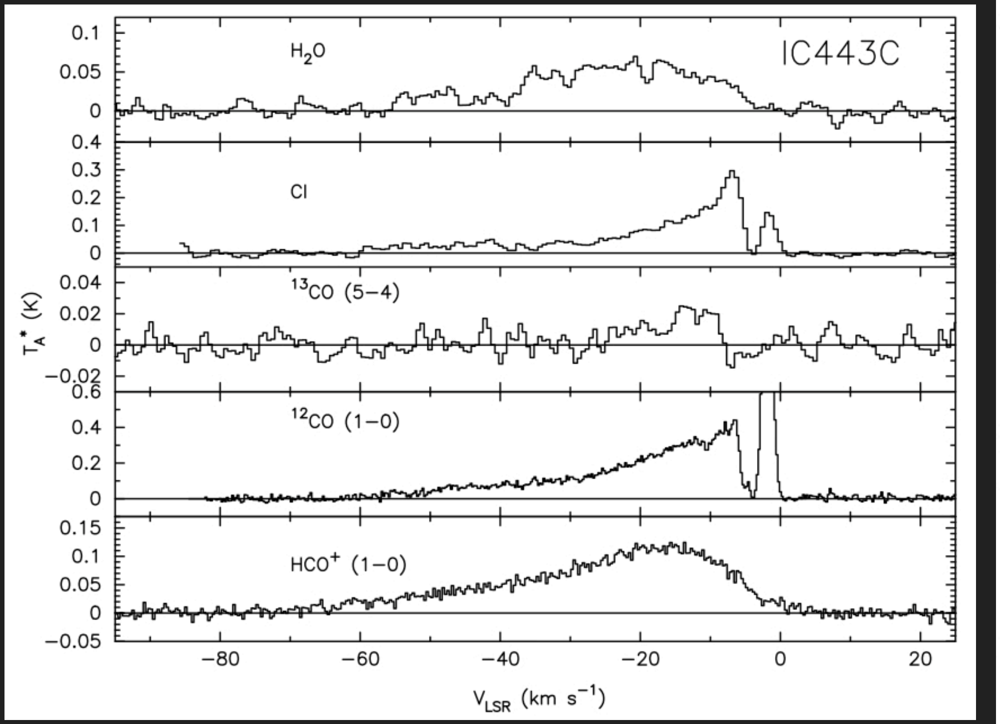
Example: IC443 SNR

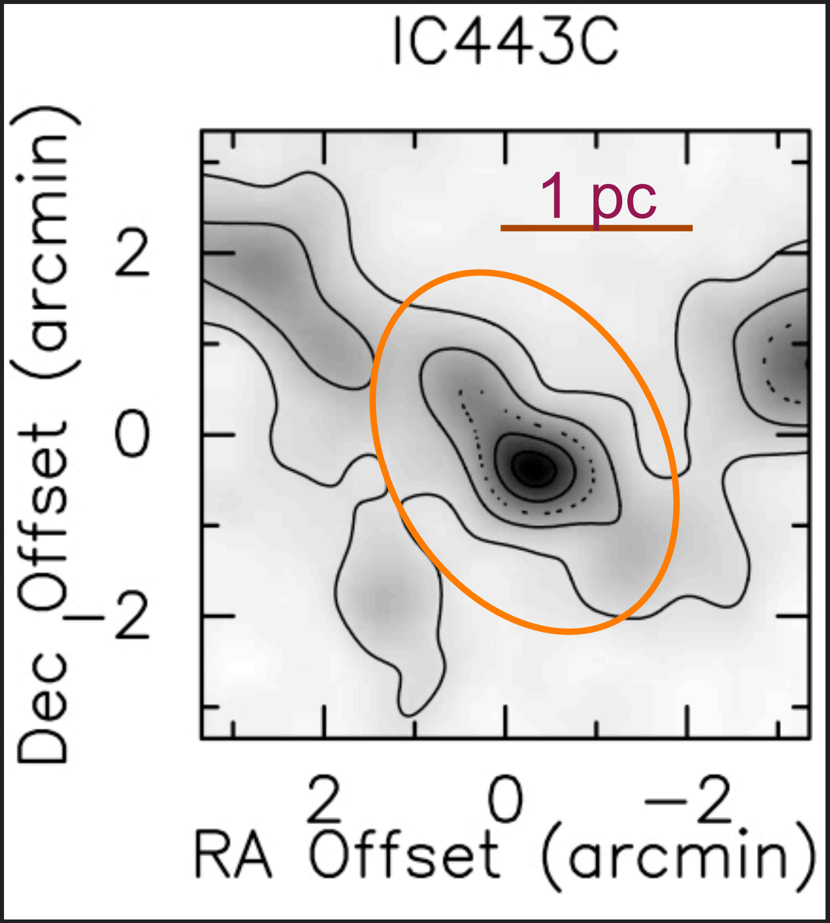


H_2 1-0S(1)
Richter 1995

- Strong H_2 2 & 12μm: emission from ~2000K gas
- Ram pressure ~ 10^7 cm^{-3} $(km/s)^2$
- HI
- Strong OI 63 μm
- Strong CII 158 μm

SWAS: IC443 SNR





H_2O 557 GHz
CI 492 GHz
^{13}CO 5-4
from SWAS

CO J=1-0 FCRAO
Snell et al. 2005

SWAS H_2O in IC443

- Beam-averaged H_2O column in effectively-thin limit ($\tau >> 1$, $n << n_{cr}$)
  $N(H_2O) \propto \int T dv / n C_{lu} \sim 2\text{-}4 \times 10^{13}$ cm^{-2}
- High res (spatial and spectral) CO
  - Measure H_2O/CO assuming water has same spatial distribution as CO and fitting n,T,$N_{peak}(H_2O) \sim 3 \times 10^{14}$ cm^{-2}
    $H_2O/CO \sim 10^{-3}$

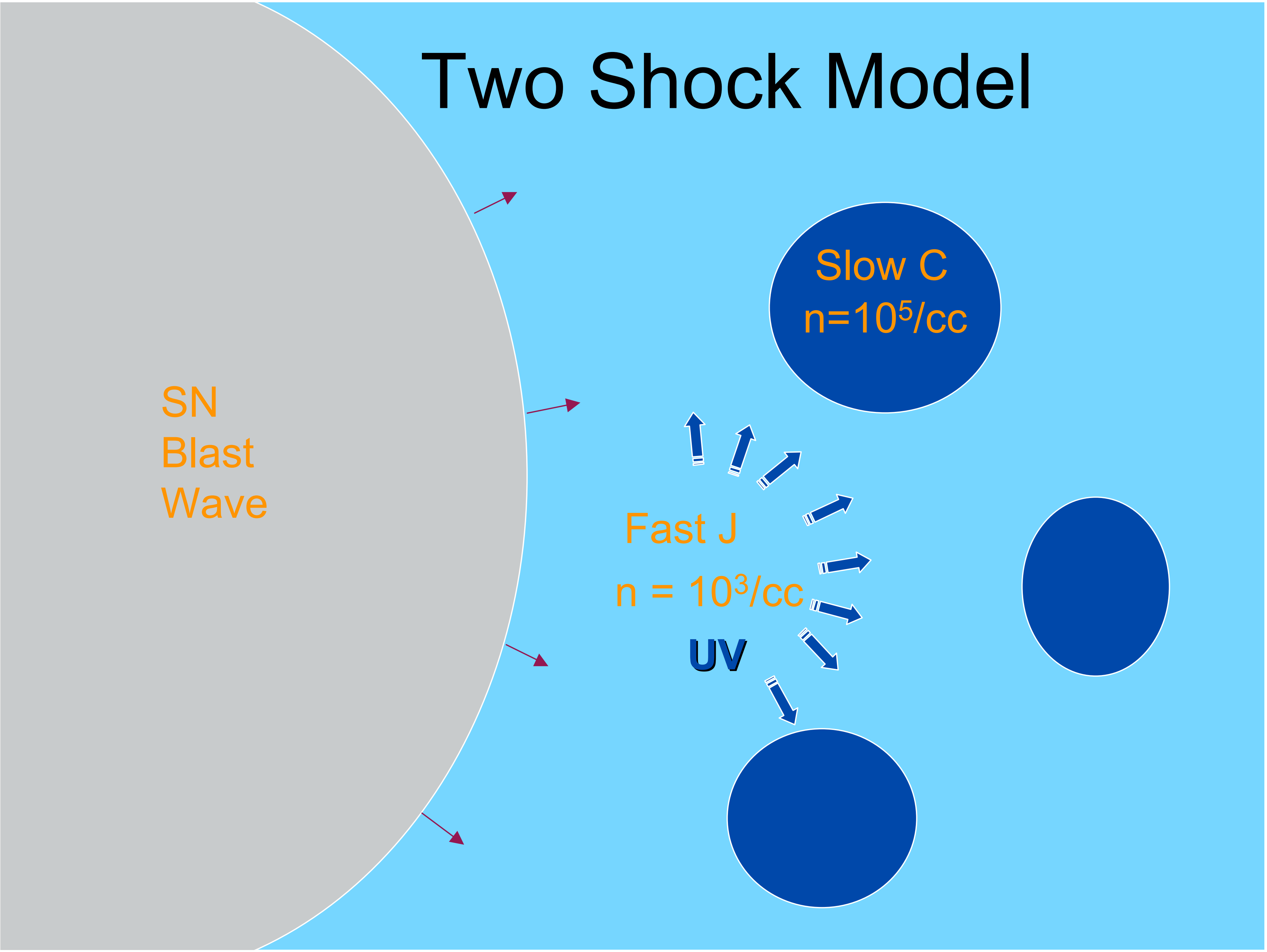
ISO Observations

- H_2O, OH, and high-J CO
- 4_{14}-3_{13}/H_2 2μm ~ 0.04 (Models: > 0.3)
- H_2O/OH ~0.1 as in 3C 391(Reach & Rho 1998): H_2O dissociated by UV?

IC443 Observation Summary

- Ram pressure ~ 10^7 cm^{-3} $(km/s)^2$
- Strong H_2 2 &12μm : emission from 2000 K gas   Fast C/Slow J
- HI   Fast J
- Strong OI 63μm   Fast J/Slow C
- Strong CII 158μm   Fast J
- Low $N(H_2O)$ Fast J/Slow C
- H_2O/OH low   UV?
- H_2O/H_2 low   Freeze out?

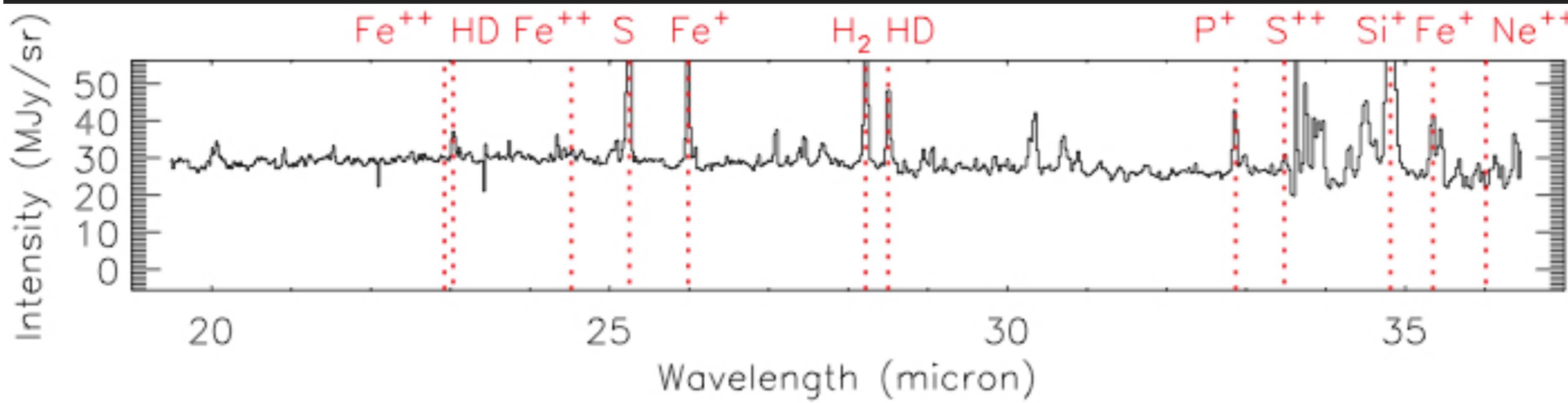
Two Shock Model

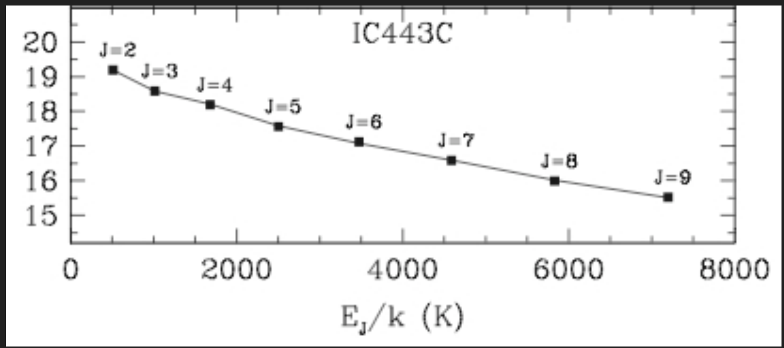


Two Shock Model

- 1 - Fast-J (~100 km/s) in inter-clump gas, $n \sim 10^3$: OI, CII, HI *and* FUV radiation ~1-10 times typical interstellar value
- 2 - Slow C with $x \sim 10^{-5}$, $n \sim 10^5$ in clumps: *Maximum speed of 12 km/s!*
  - H_2O suppressed by FUV dissociation once $T < 300$ K
  - In addition, about 1/2 of available OI must be frozen out preshock ==> slow shock so ice isn't sputtered off grains!

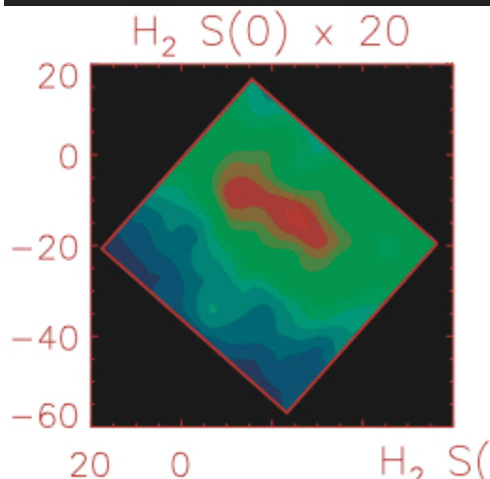
IC443 with Spitzer/IRS



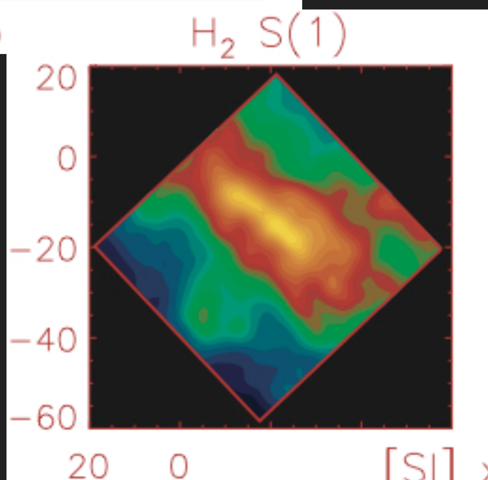


Neufeld et al. 2007

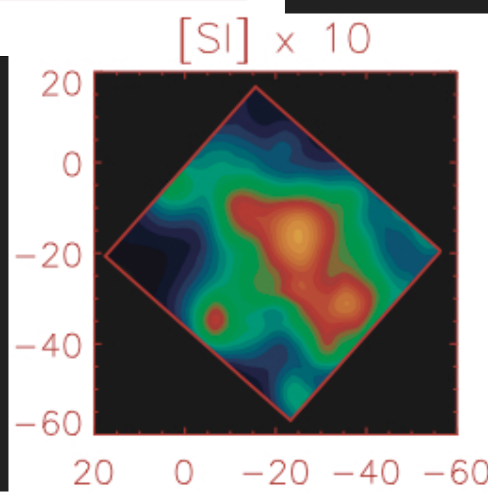
IC443 SNR



H_2 S(0)

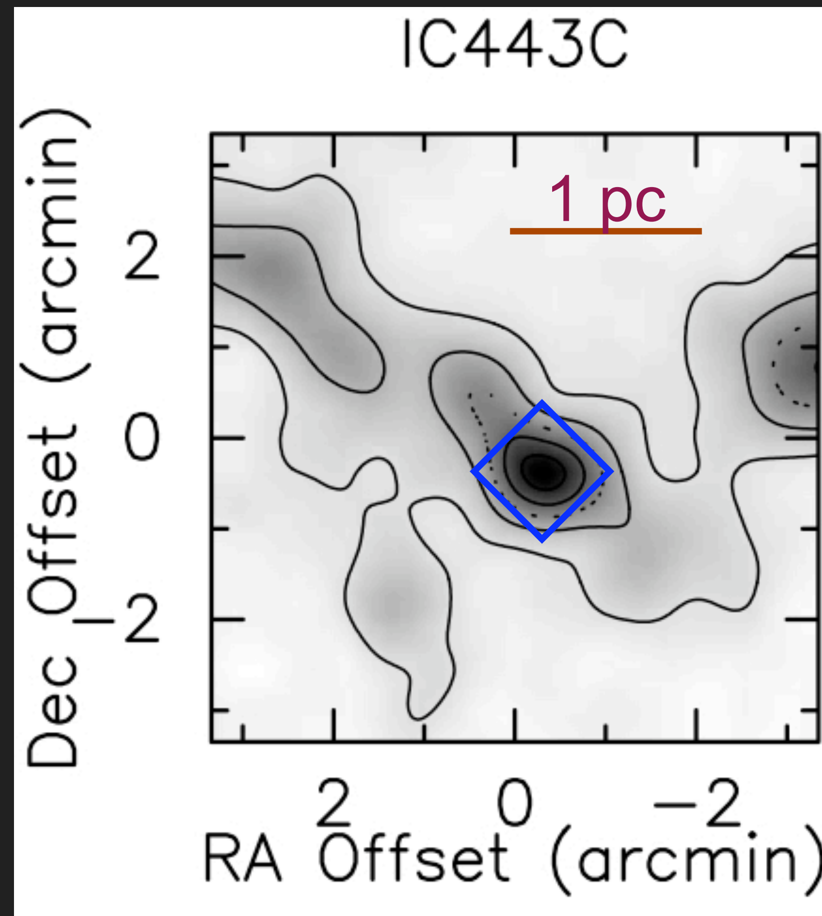


H_2 S(1)



SI

Spitzer/IRS
Neufeld et al.
2007



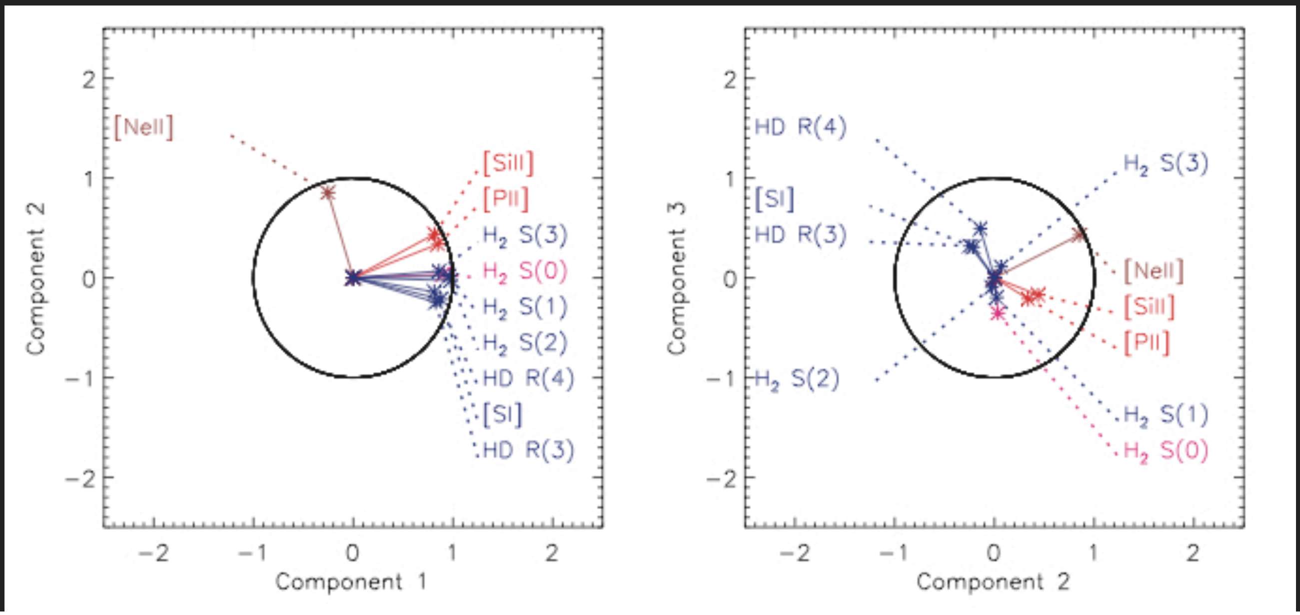
CO J=1-0 FCRAO
Snell et al. 2005

PC Analysis

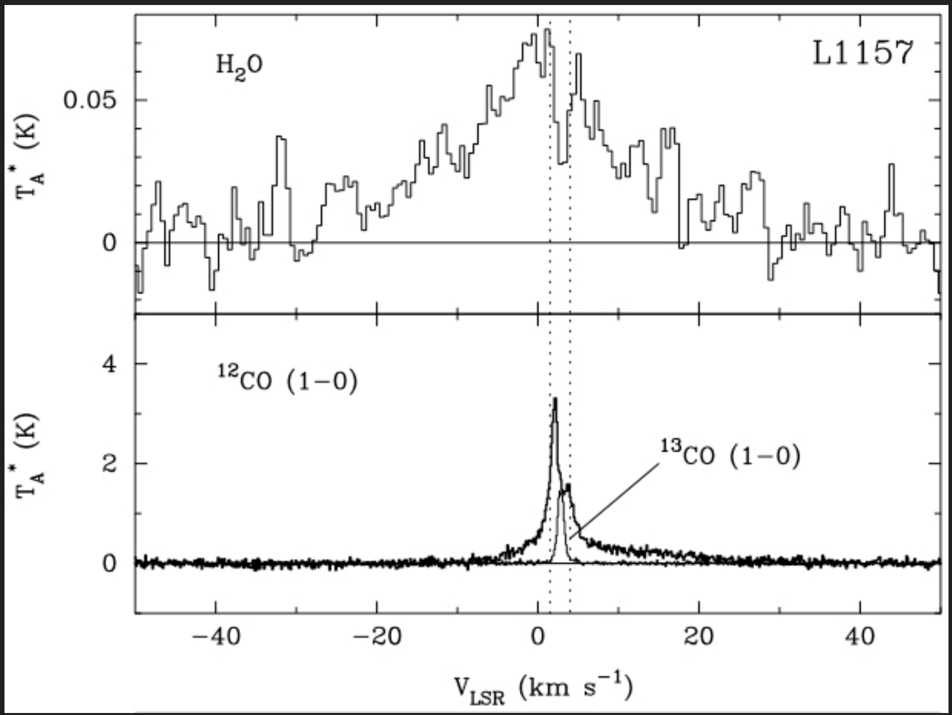
Basis set to characterize spatial variations in the maps

Molecular emission distinct from regions producing fine structure ionic emission

==> Multiple shocks?



Observations of YSO Outflows



SWAS: Franklin et al. 2008

- 17 Sources, both high and low mass
- High spectral resolution H_2O 557 GHz, CO J=1-0, ^{13}CO J=1-0
- Compare gas masses as a function of velocity

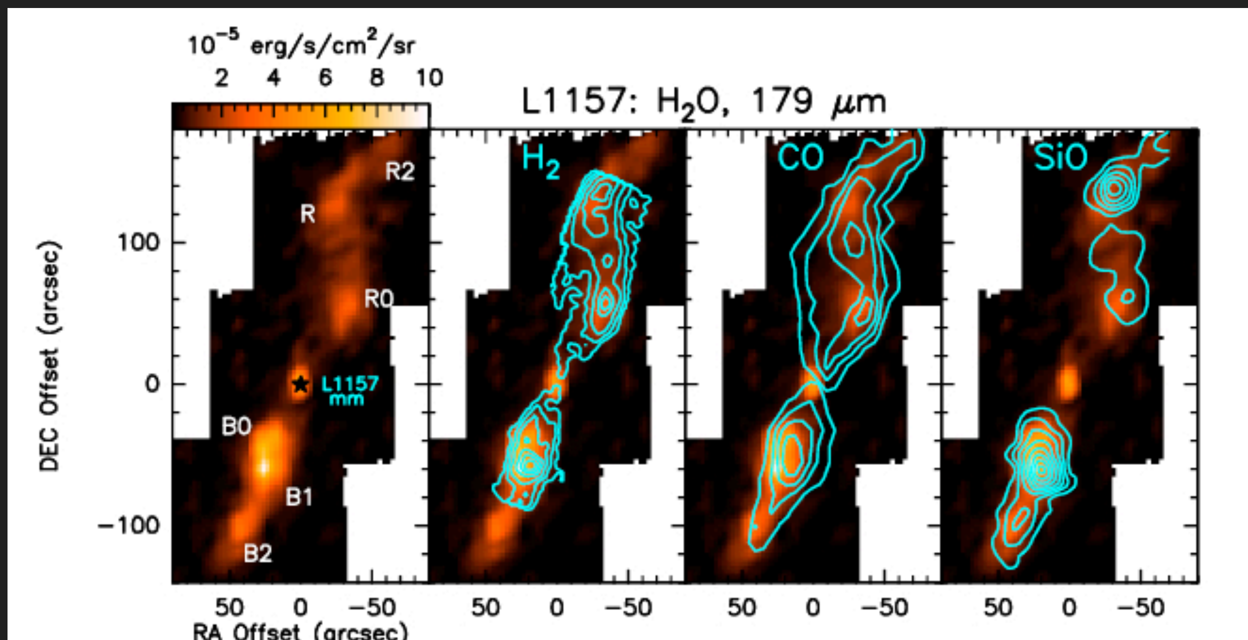
Water abundance per velocity

Source		V_{LSR} Interval ($km\ s^{-1}$)	H_2O Line Flux[a] (10^{-20} W cm^{-2})	Mass ($M_\odot$)	o-H_2O Abundance[b]
L1157	Blue	-13.5 → 1.5	1.84 (0.06)	4.1×10^{-1}	8.0×10^{-6}
	Red	4.0 → 29.0	1.58 (0.08)	3.2×10^{-1}	9.7×10^{-6}
L1157	Blue	-3.5 → 1.5	0.86 (0.04)	2.8×10^{-1}	5.3×10^{-6}
		-8.5 → -3.5	0.58 (0.04)	1.9×10^{-2}	4.9×10^{-5}
		-13.5 → -8.5	0.40 (0.04)	3.9×10^{-3}	3.5×10^{-4}
	Red	4.0 → 9.0	0.59 (0.04)	2.9×10^{-1}	3.8×10^{-6}
		9.0 → 14.0	0.37 (0.04)	5.2×10^{-2}	1.3×10^{-5}
		14.0 → 19.0	0.28 (0.04)	3.6×10^{-2}	1.5×10^{-5}
		19.0 → 24.0	0.16 (0.04)	2.0×10^{-2}	1.6×10^{-5}
		24.0 → 29.0	0.18 (0.04)	7.0×10^{-3}	5.2×10^{-5}

ISO Observations of L1157

- Detections of H_2O 179μm and CO J=20-19, J=15-14
- CO line ratio: temperature → v ~ 30 km/s
- CO J=15-14/179μm: density → n ~ 10^5 cm^{-3}
- Solid angle required to match emission is tiny ~ 10 $arcsec^2$
- Only $5x10^{-3}$ $M_{\odot}$, about 1% of outflow mass, has been shocked sufficiently to drive up H_2O abundance

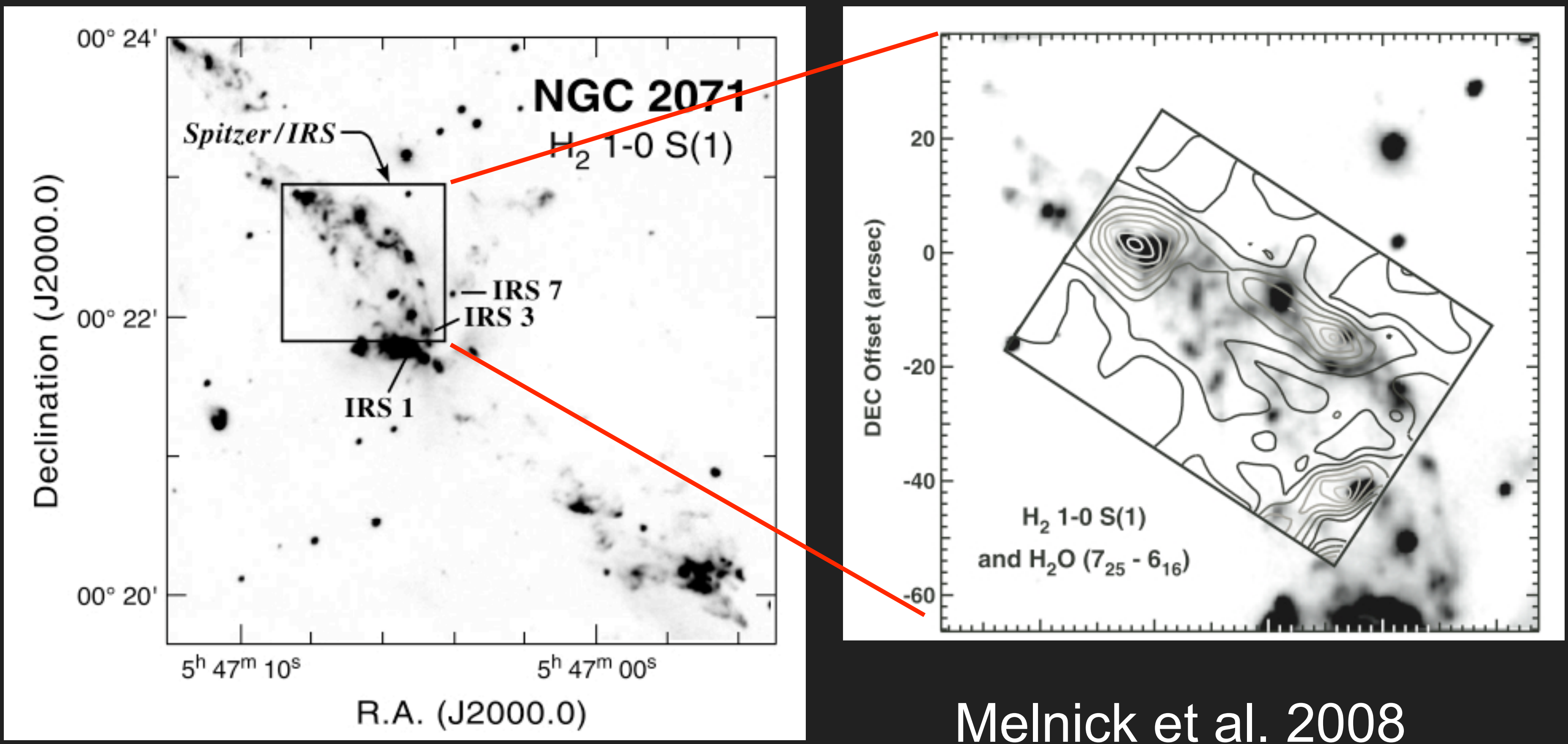
Shocked H_2O Mapped in 1157



Nisini et al. 2010

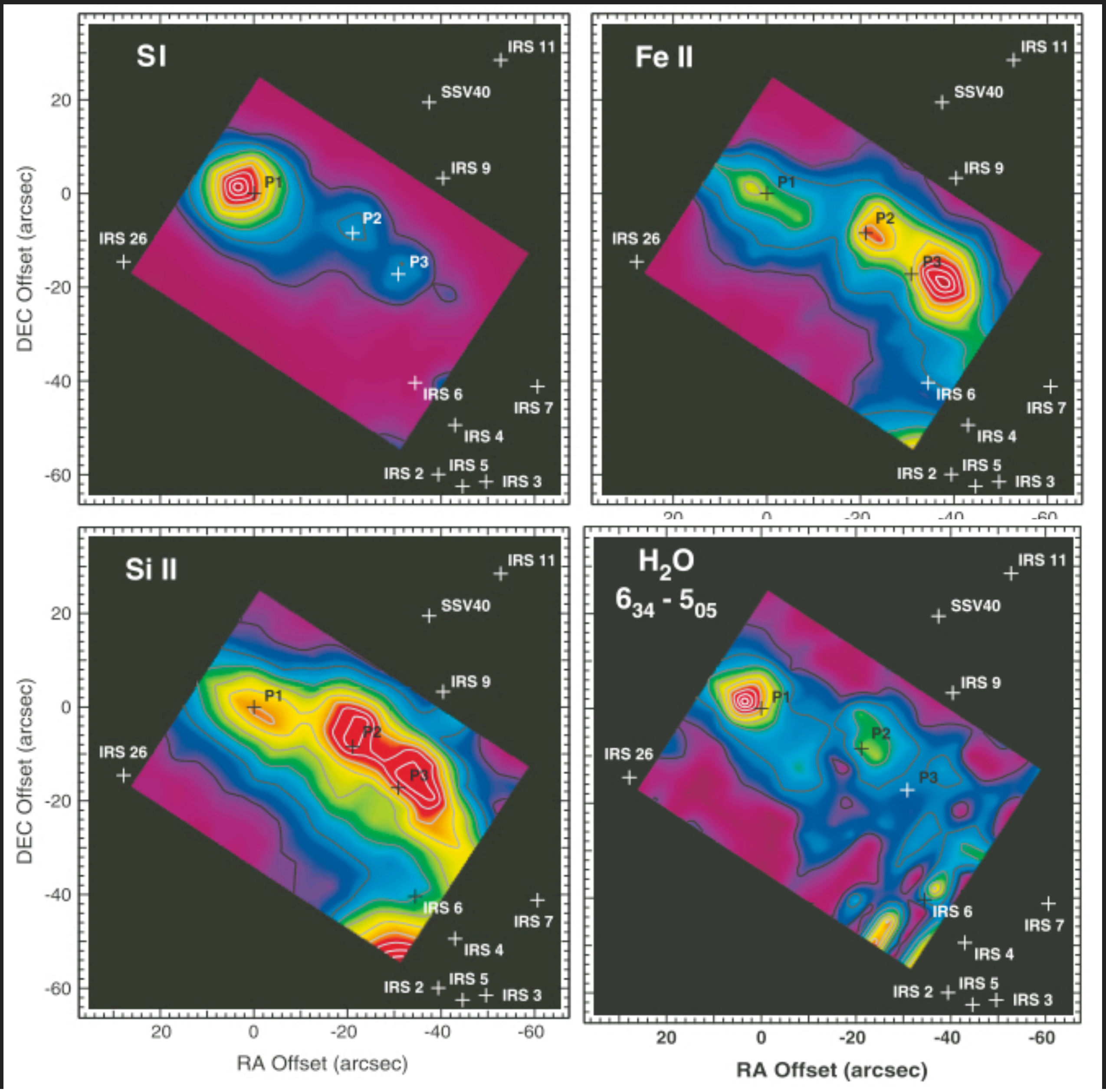
25% of shock cooling in H_2O lines

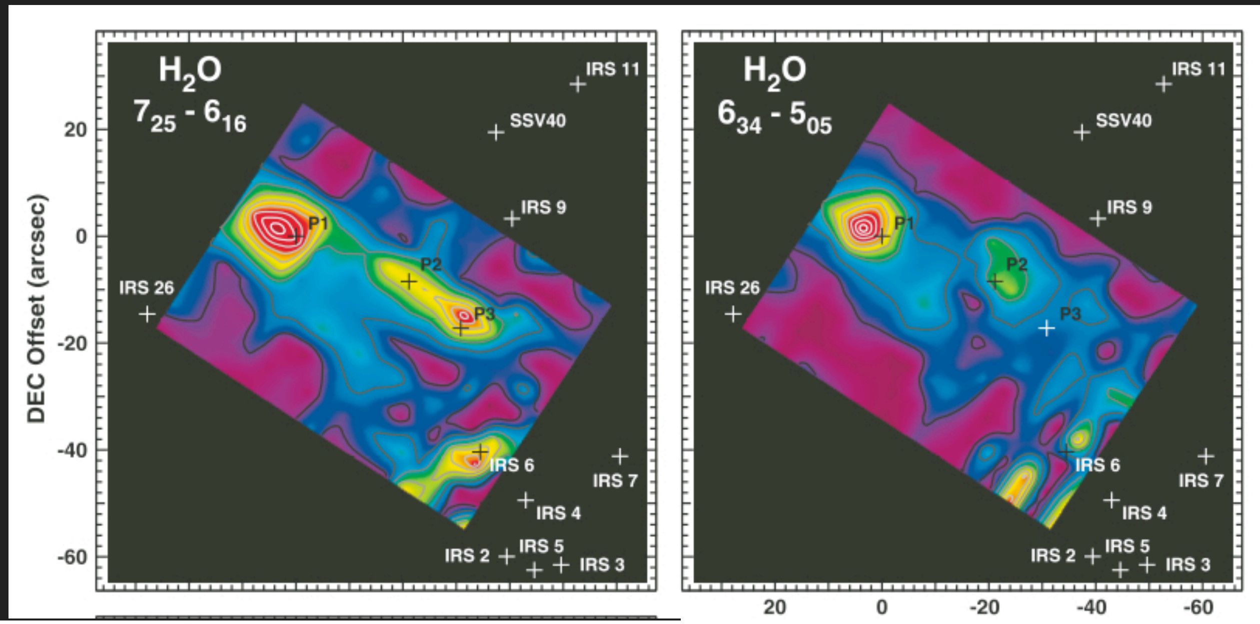
Spitzer Observations of NGC2071: Spatial Information



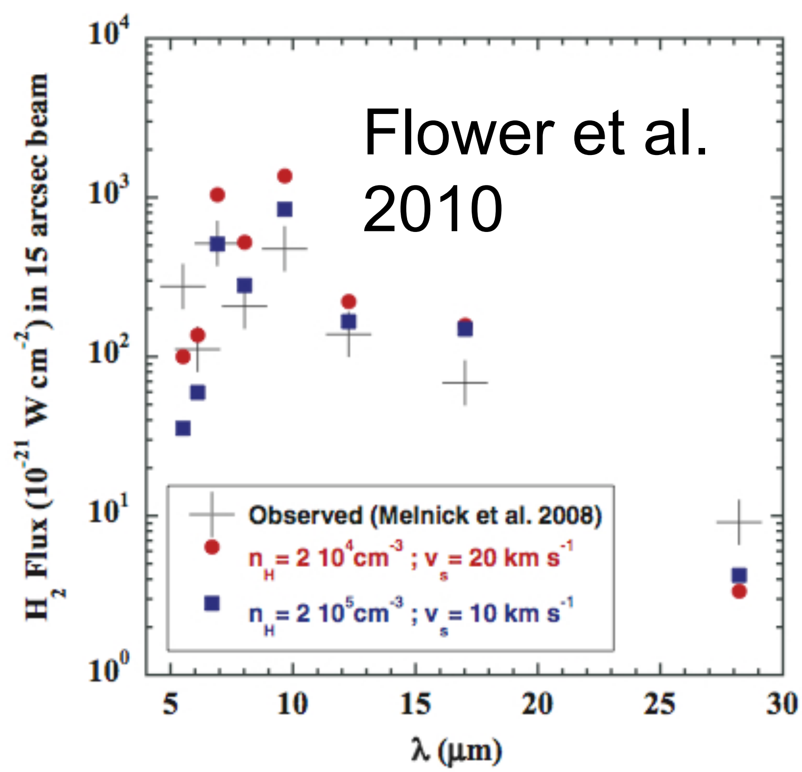
Melnick et al. 2008

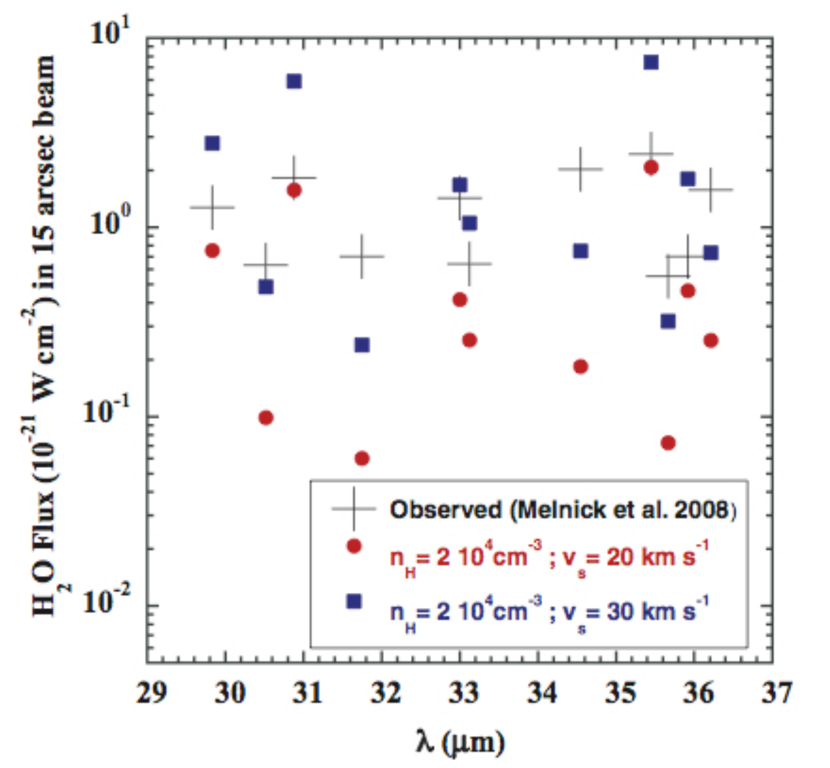
Separation of J and C Tracers



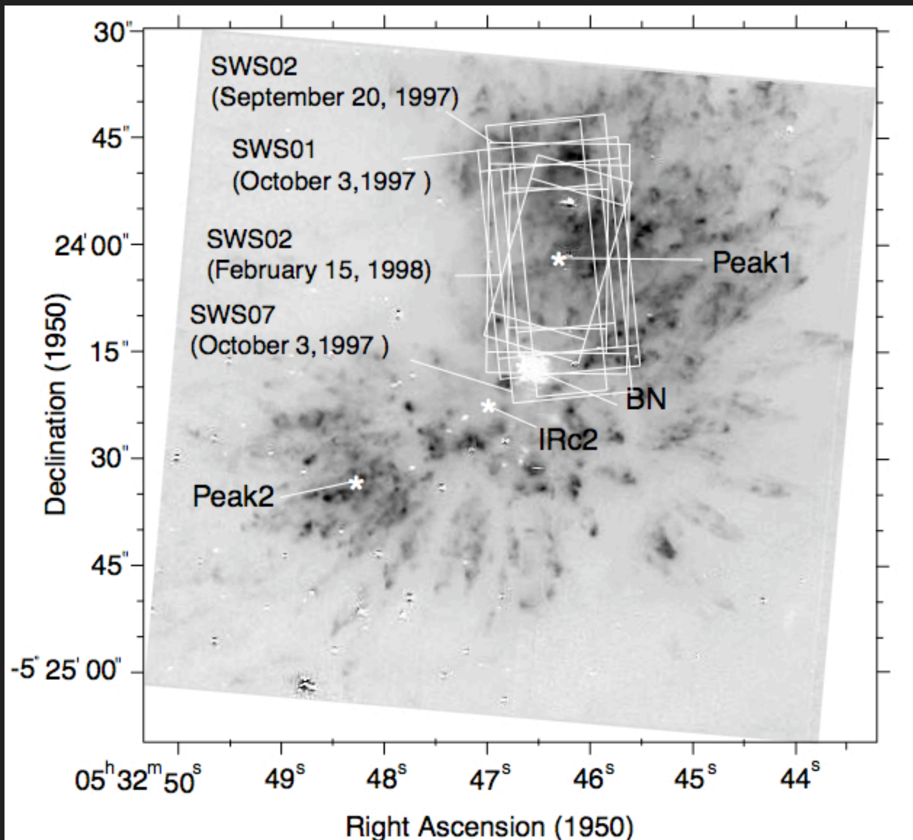


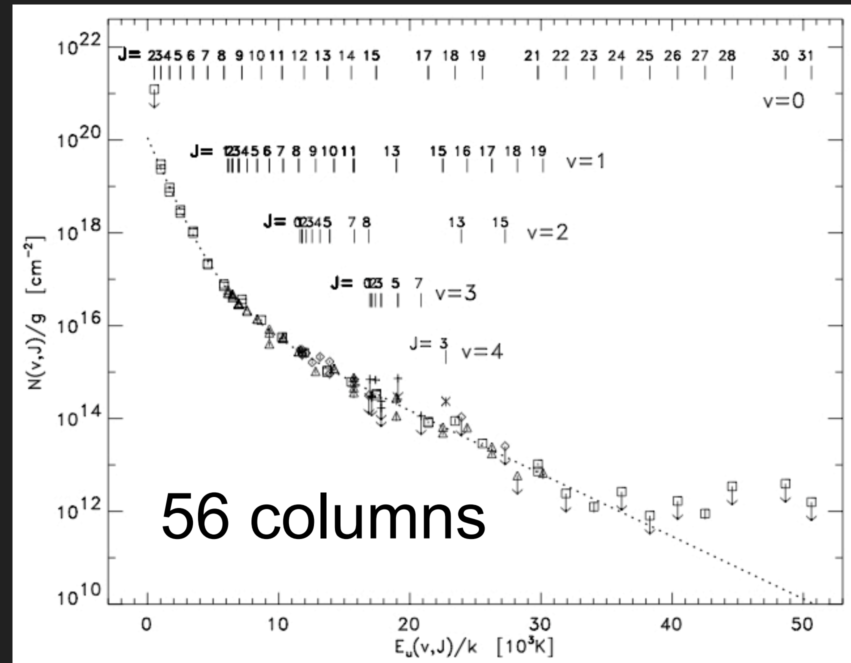
Flower et al. 2010

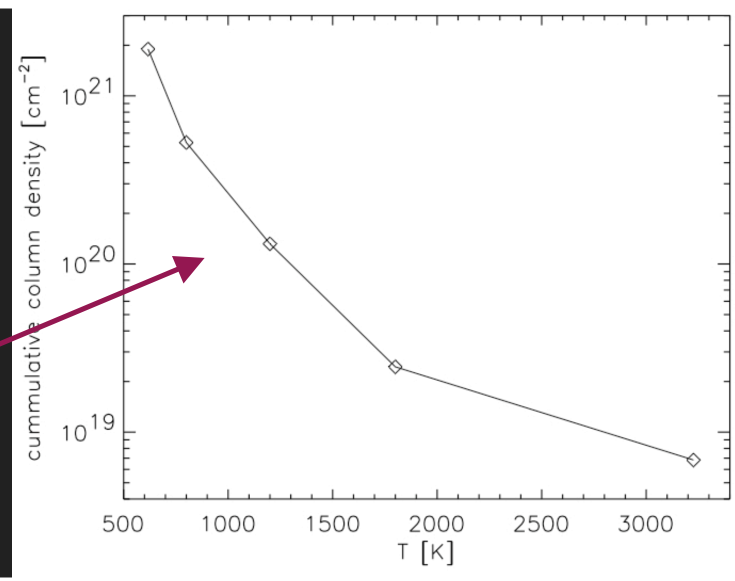




Shocked H_2 in Orion



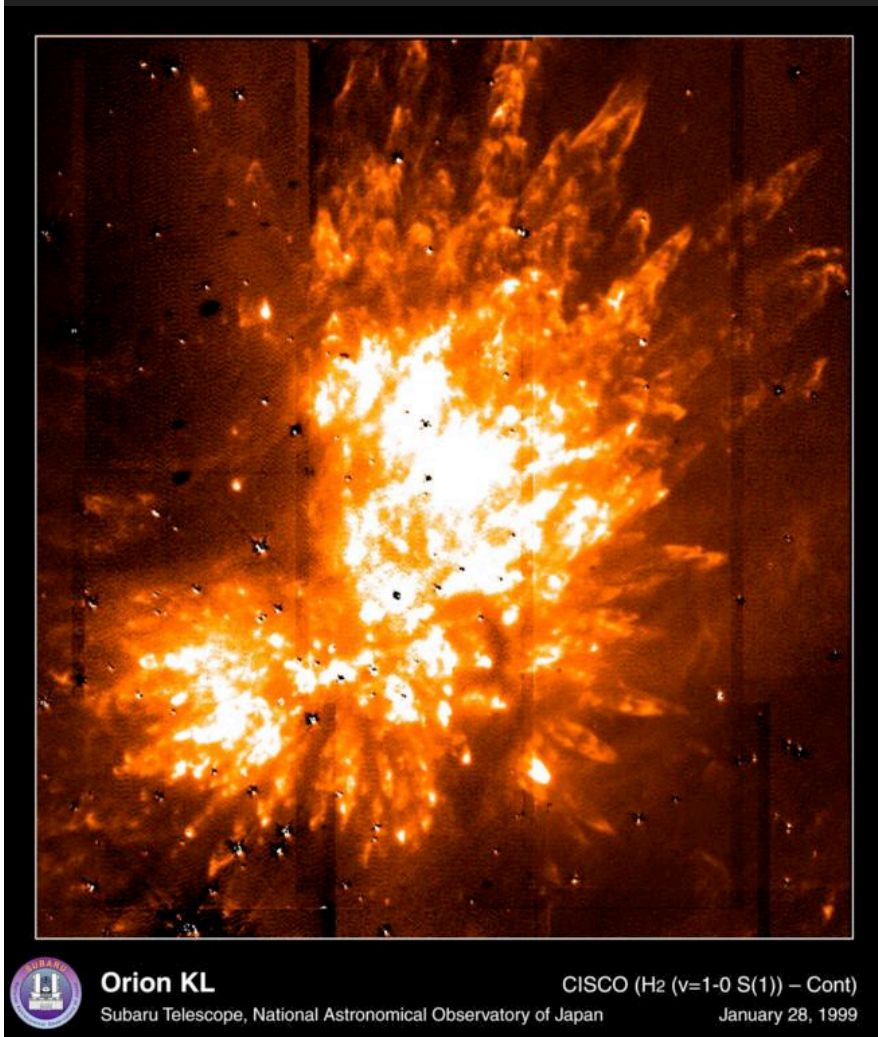


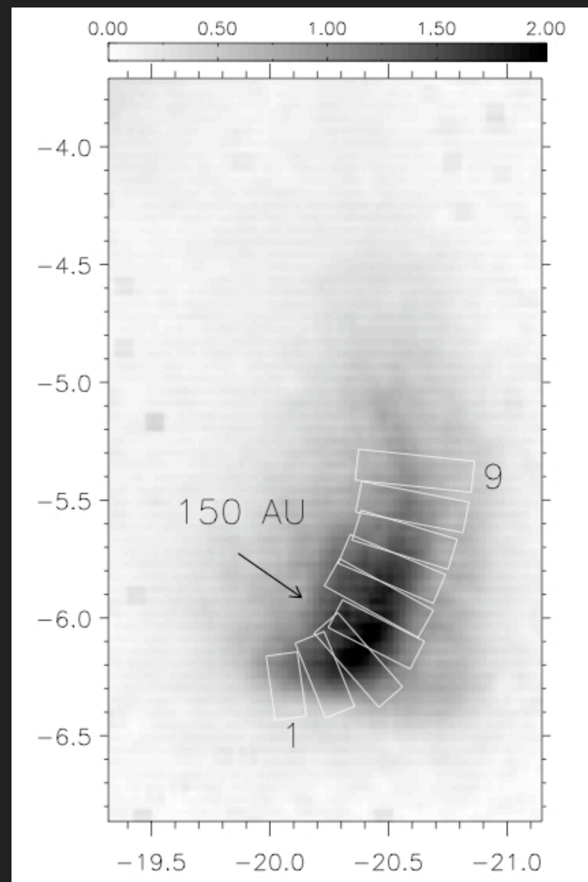


Rosenthal et al. 2000

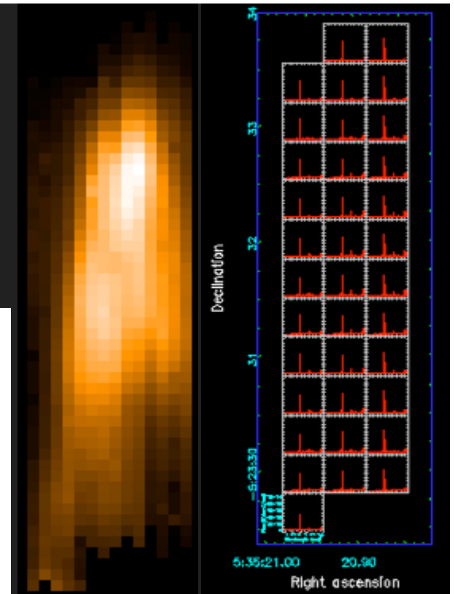
Multiple shocks needed to match column densities

Bow Shocks in Orion



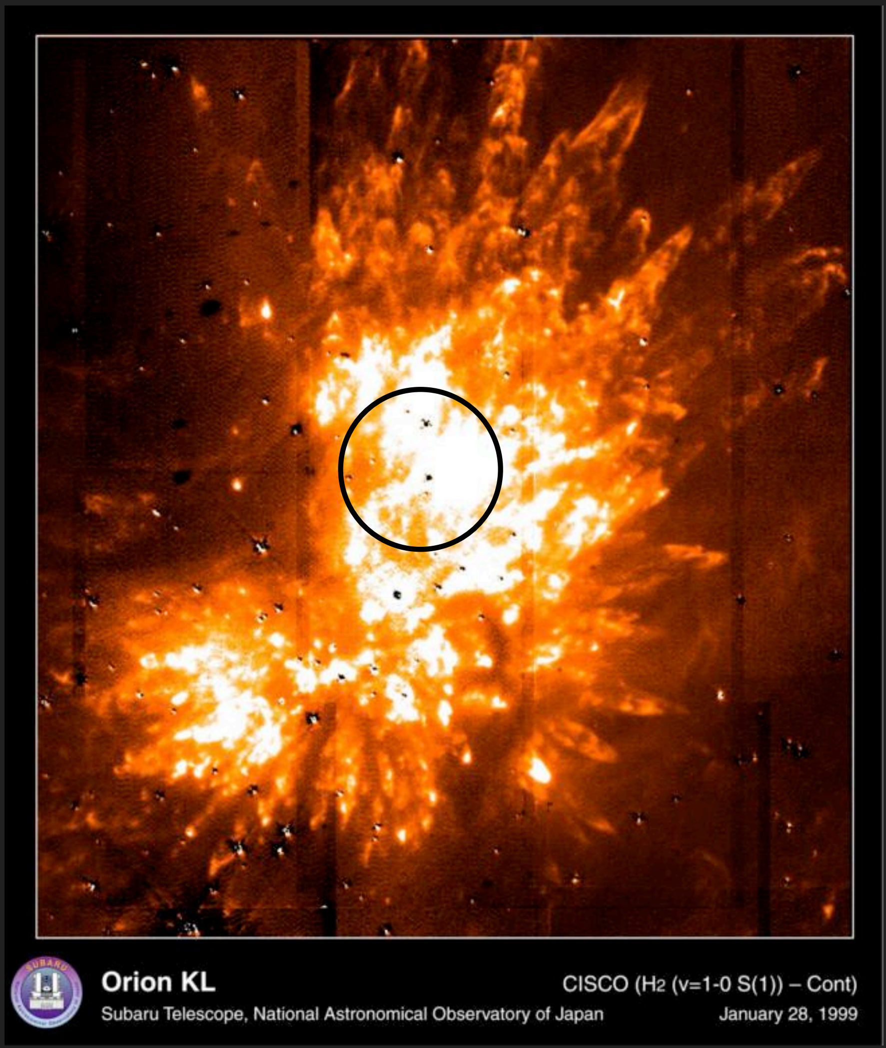


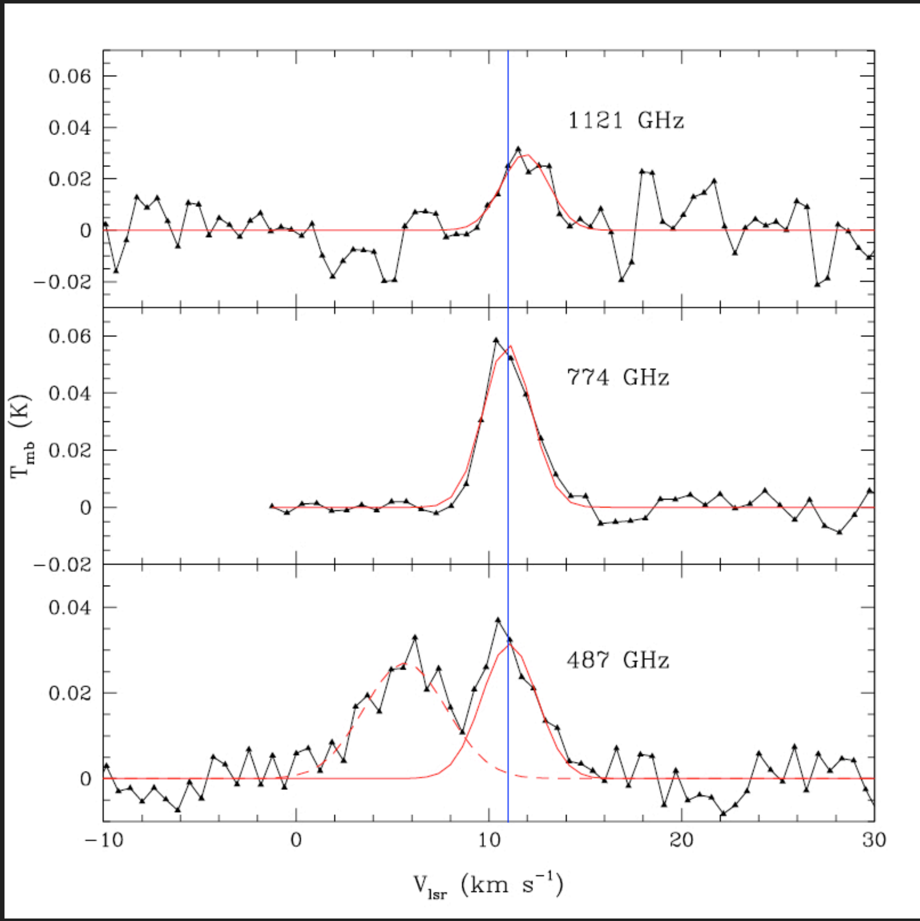
Kristensen et al. 2008



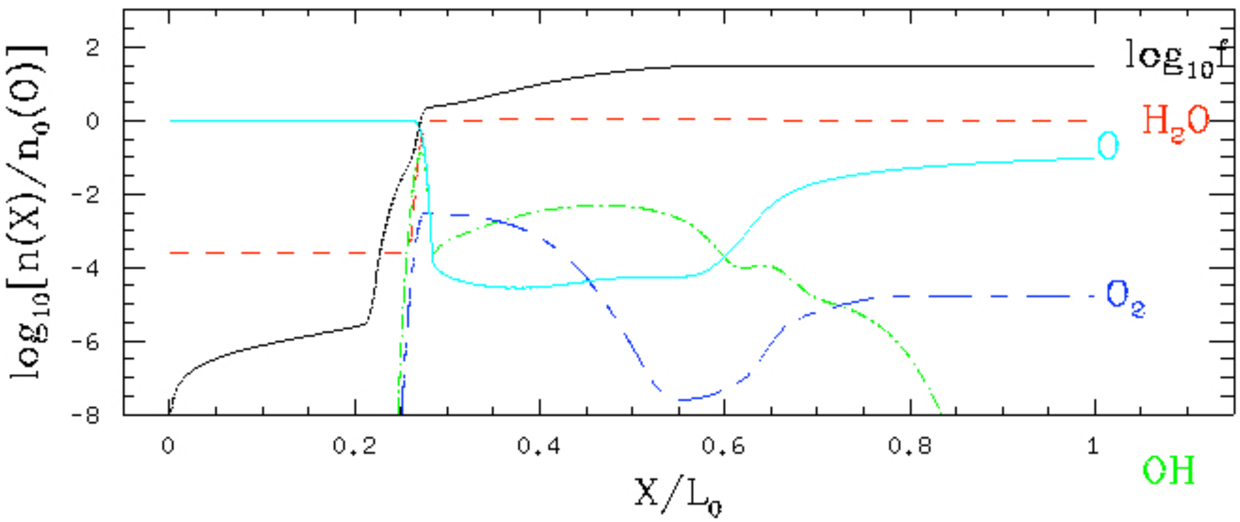
Olson et al. 2010

HOP O_2 Emission Lines: Pk 1





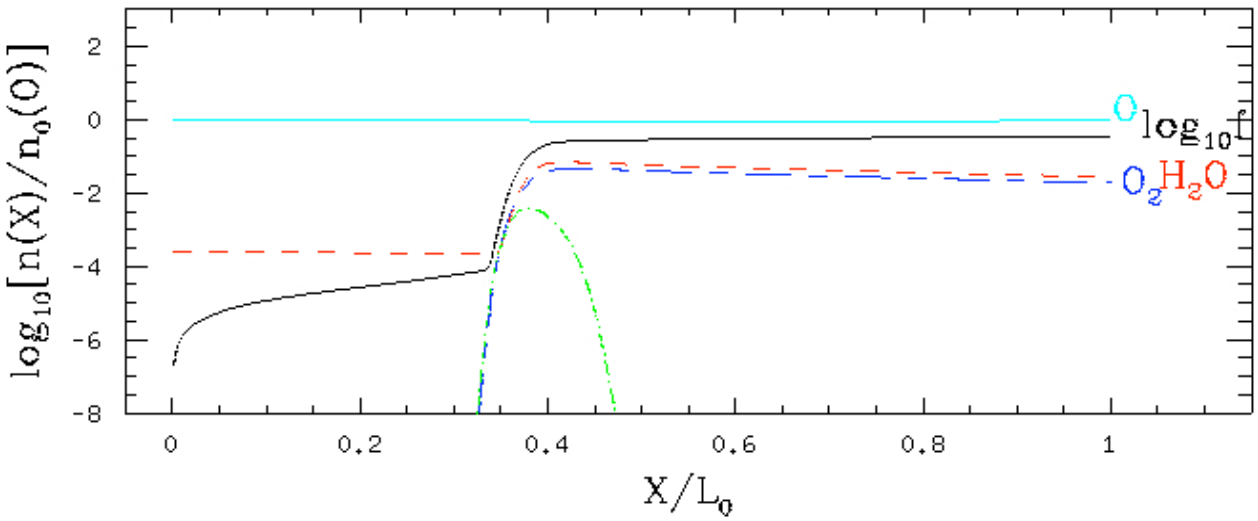
Low Velocity Shocks Are Better For O_2



$V = 40$ km/s

$T_{max} \sim 3000$ K

$N(O_2) \sim 4 \times 10^{13}$

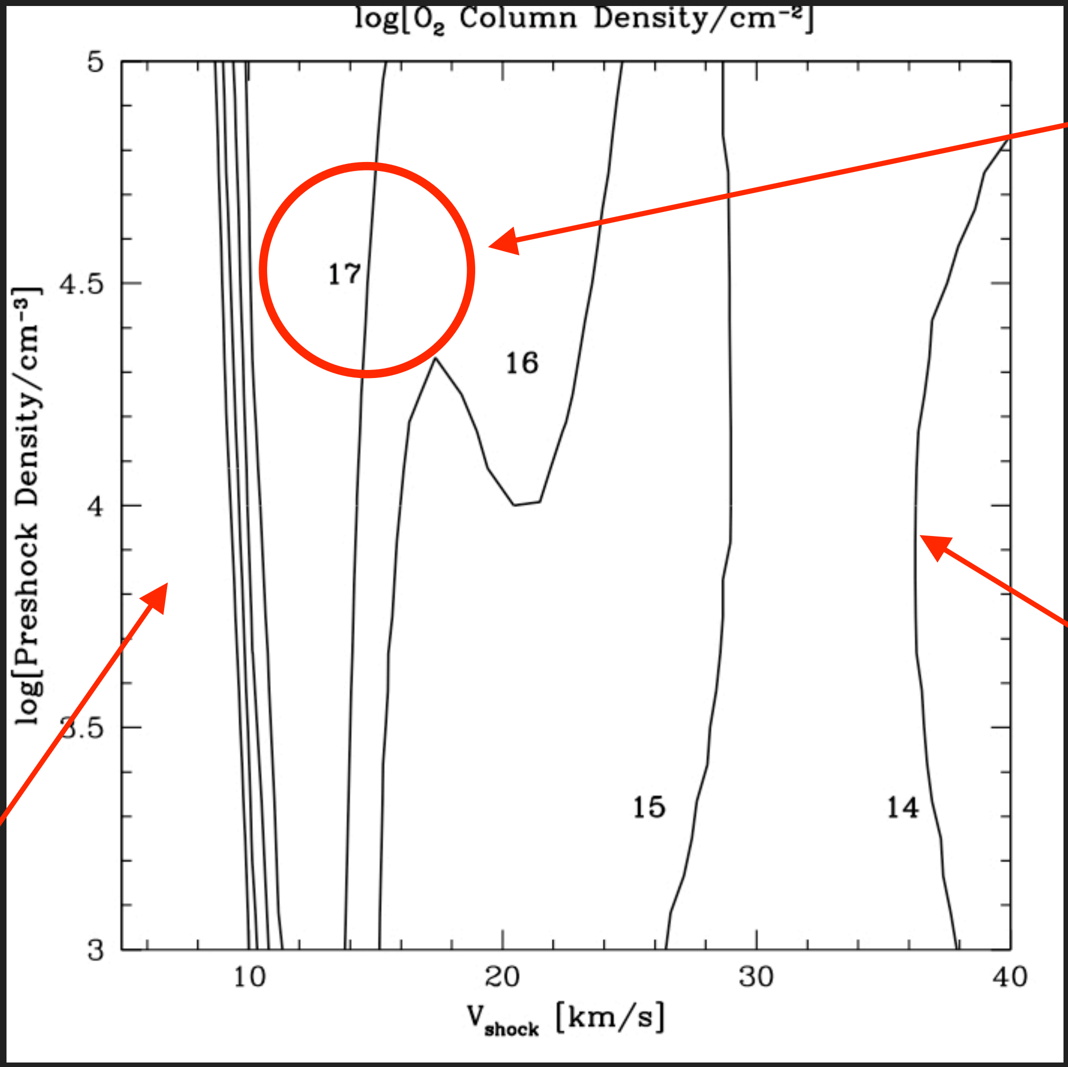


$V = 10$ km/s

$T_{max} \sim 400$ K

$N(O_2) \sim 10^{16}$

O_2 Column Density in C-Shocks



Density

"Sweet spot"

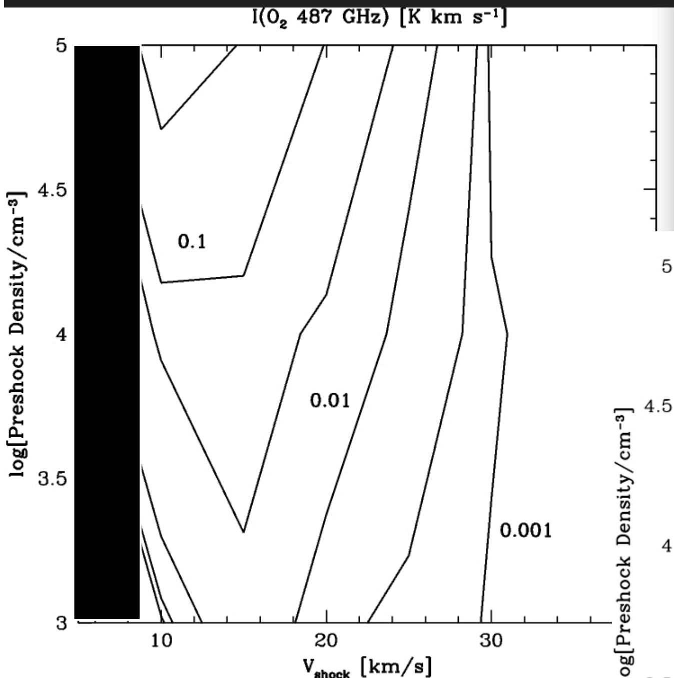
O driven into H_2O

Too cold for OH formation

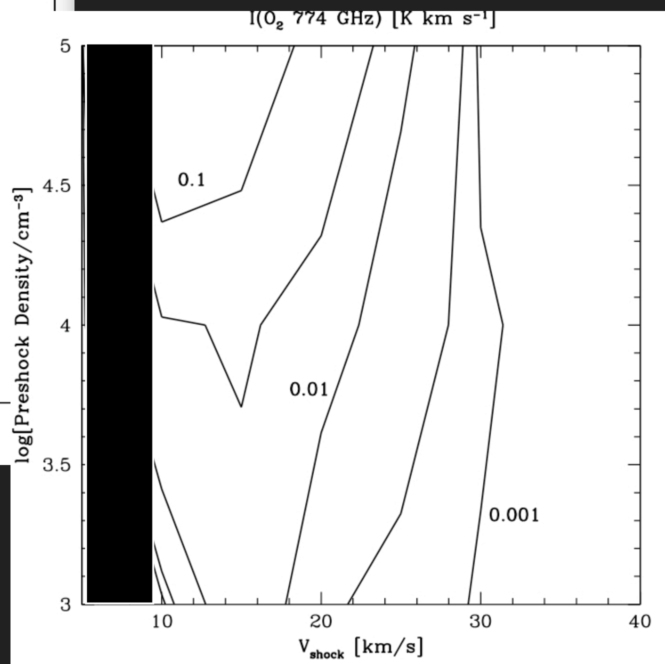
Shock Velocity

O_2 Line Intensities

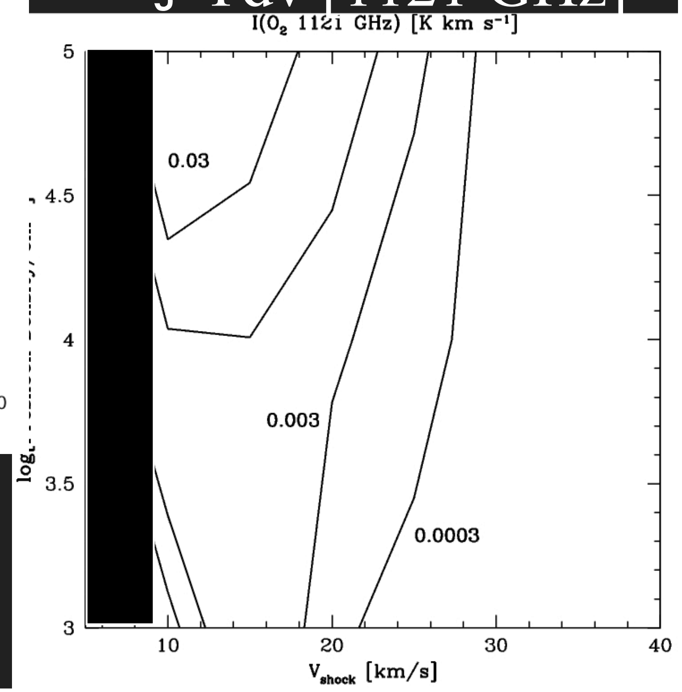
∫ Tdv [487 GHz]



∫ Tdv [774 GHz]



∫ Tdv [1121 GHz]



Conclusions

- Shocks come in two basic types
- Rarely is a single planar shock the answer → admixtures, including non-standard initial conditions, are more likely
- Chemical signatures of different shocks give them away
- The chemistry of H_2O and O_2 keeps getting more interesting……