Evolved Stars

Nimesh A. Patel

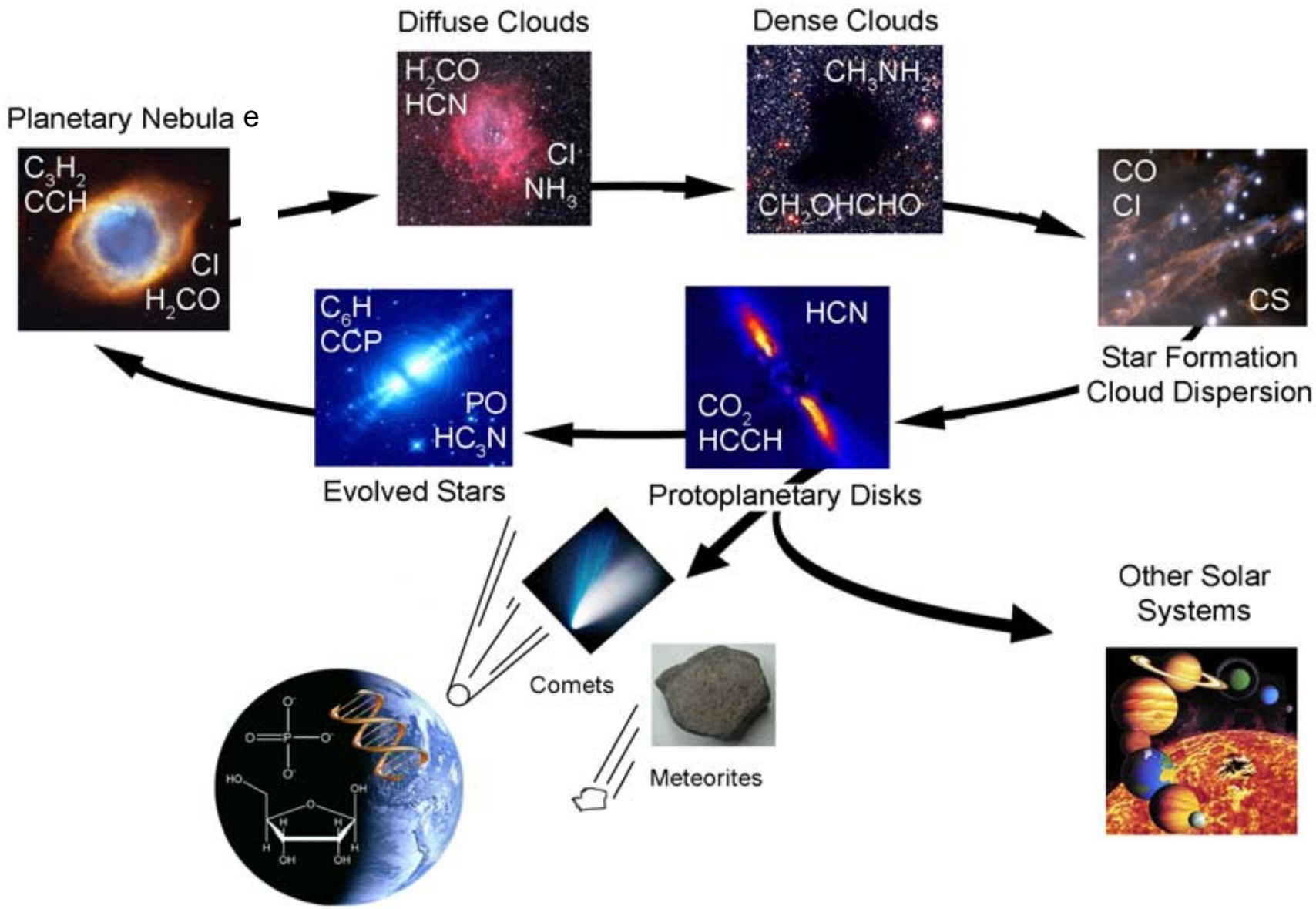
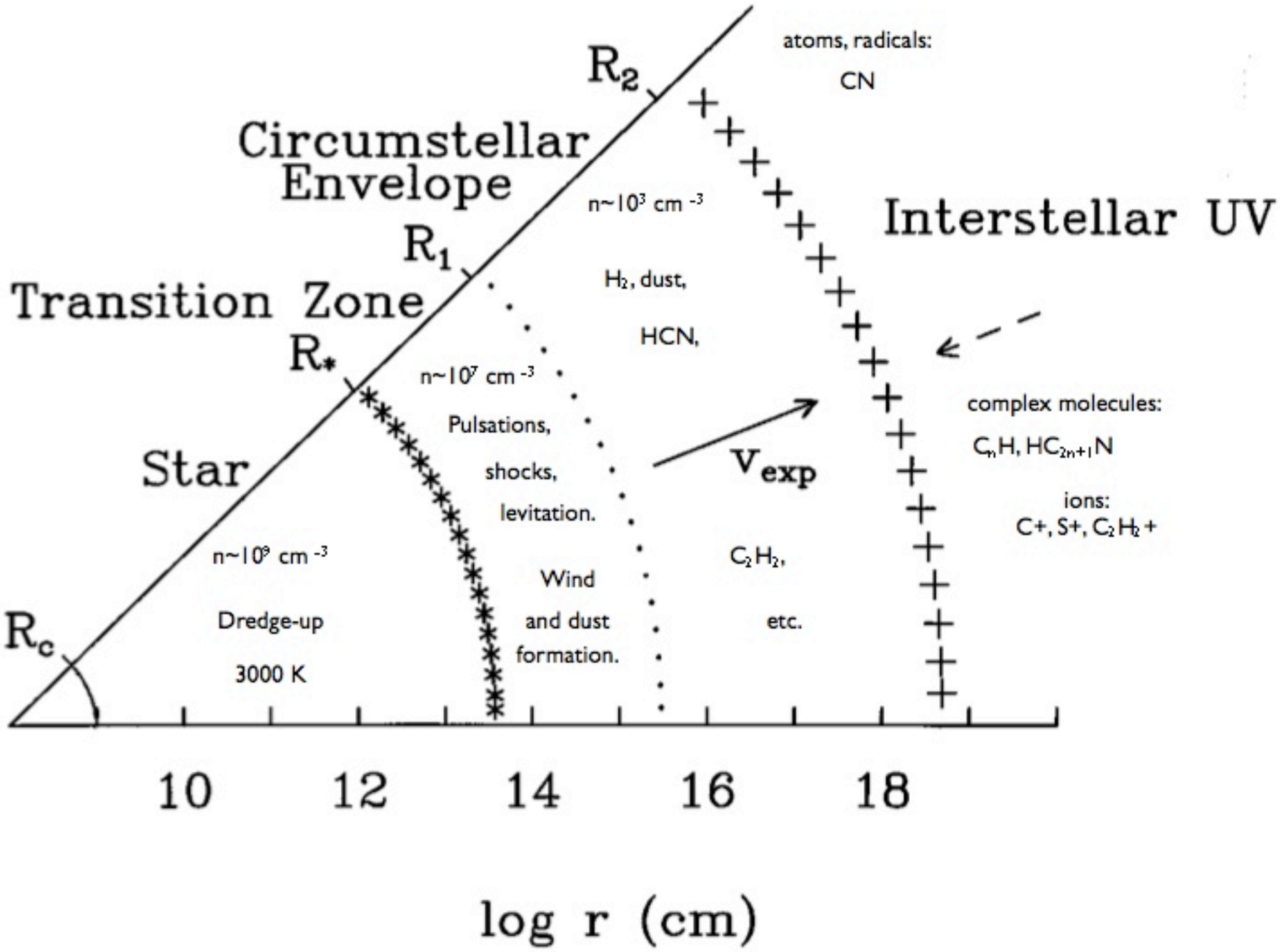
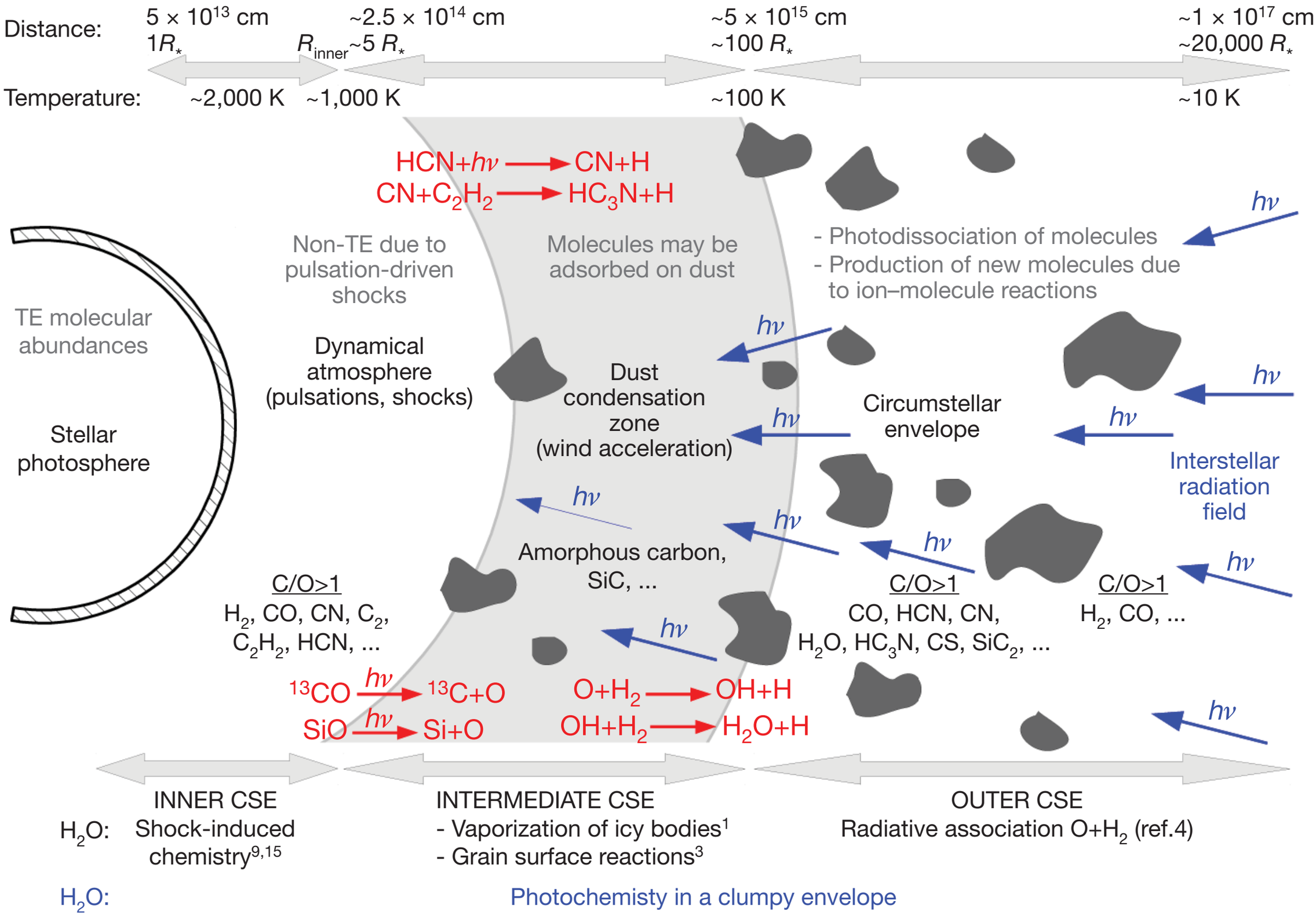


Figure 1: The life cycle of the interstellar medium and its relationship to planets and solar systems, as traced by molecular material.

Ziurys et al. 2010, Astro2010 Science White Paper


R2
Circumstellar
Envelope
R1
Transition Zone
R*
Star
Rc
n~10³ cm⁻³
H2, dust,
HCN,
n~10⁷ cm⁻³
Pulsations,
shocks,
levitation.
n~10⁹ cm⁻³
Dredge-up
3000 K
Wind
and dust
formation.
Vexp
atoms, radicals:
CN
Interstellar UV
complex molecules:
CnH, HC2n+1N
ions:
C+, S+, C2H2+
C2H2,
etc.
10
12
14
16
18
log r (cm)



Decin et al., 2010, Nature, 467, 64

SMA Papers on Evolved Stars published since Oct. 2007

Structure and Kinematics of Proto-Planetary Nebulae

Nakashima, J., Fong, D., Hasegawa T., et al., 2007, AJ, 134, 2035
Peretto N., Fuller G., Zijlstra A. & Patel N.A., 2007, A&A, 473, 207
Nakashima, J., Koning N., Kwok, S., Zhang, Y., 2009, ApJ, 692, 402
Dinh-Van-Trung, 2009a, ApJ, 692, 1382
Nakashima, J., Kwok, S., Zhang, Y., Koning, N., 2010, AJ, 140, 490

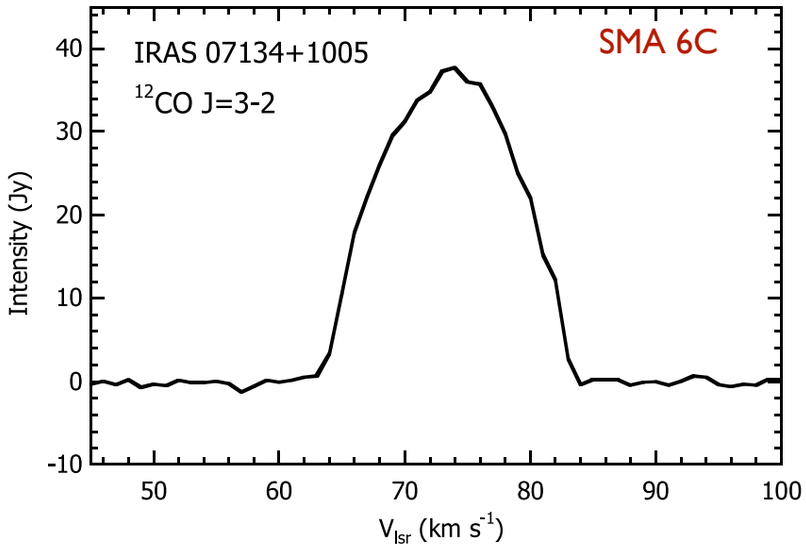
Moss Loss process

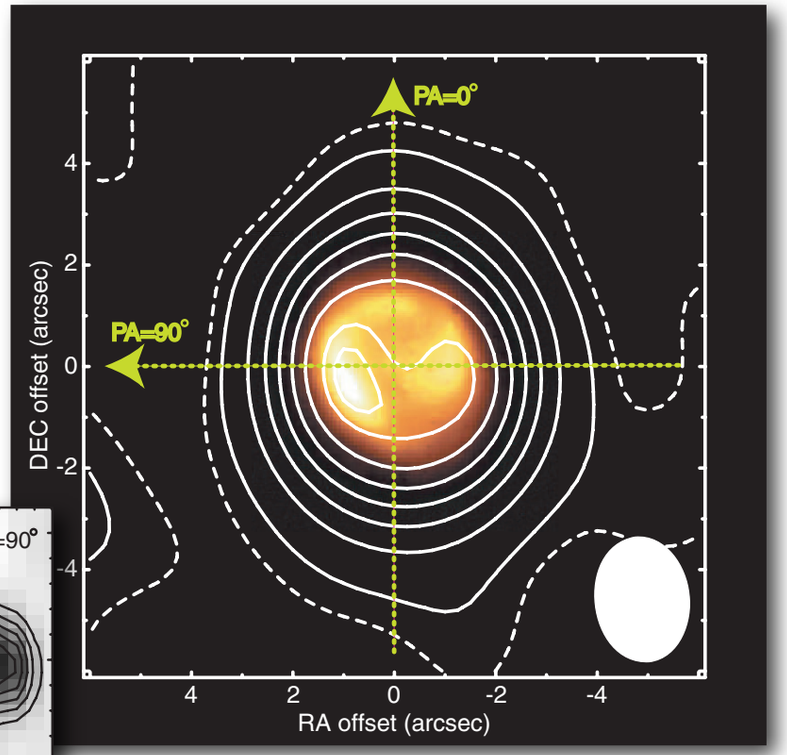
Muller S., Dinh-V-Trung, He, J., Lim J., 2008, ApJ, 684, 33
Dinh-V-Trung, Bujarrabal V., et al., 2008, ApJ, 673, 934
Winnberg, A., Deguchi, S., Reid, M., 2009, A&A, 487, 177

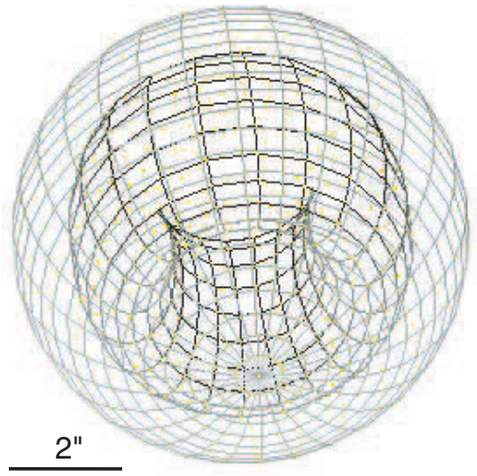
Probing the inner envelope

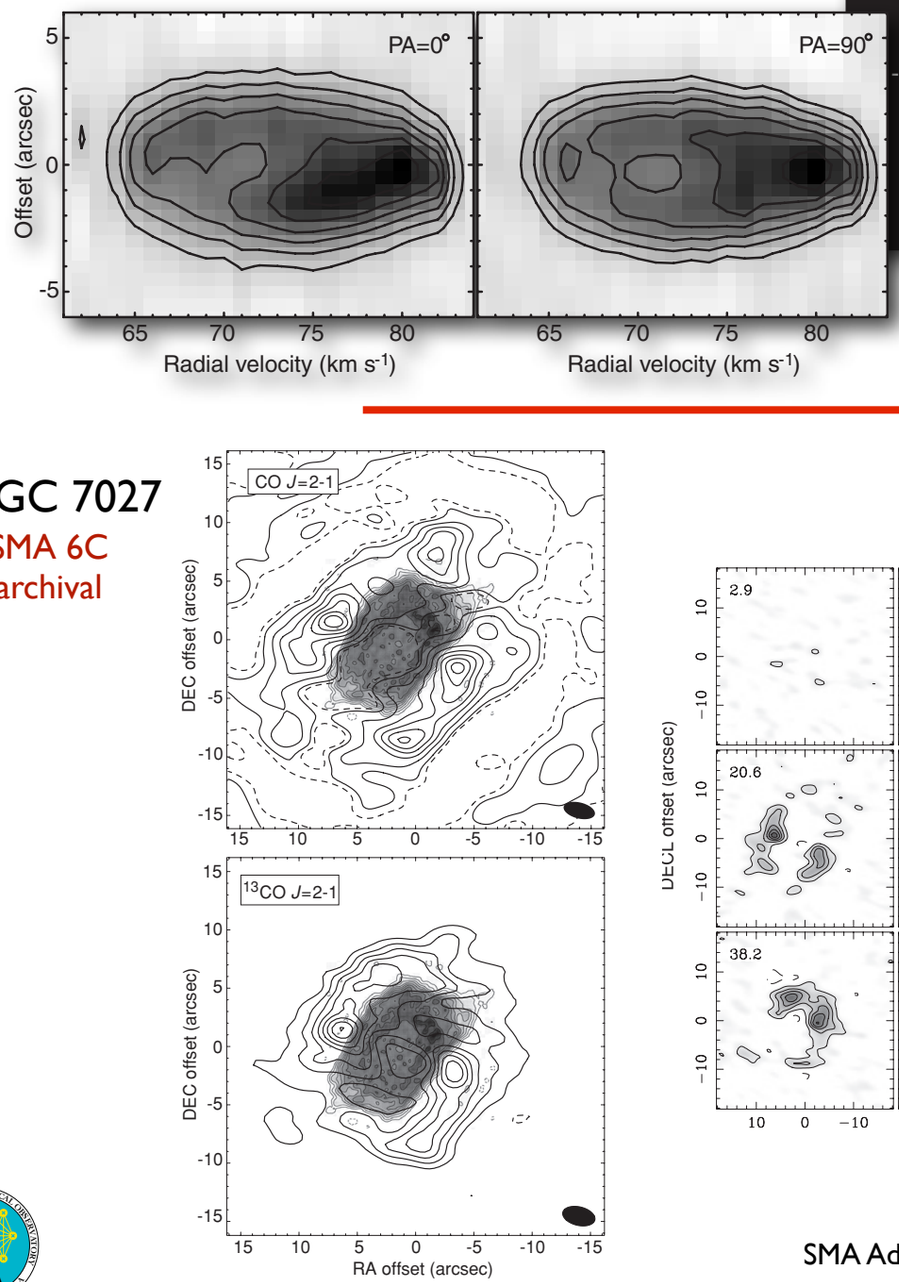
Shinnaga H., Young K., Tilanus R, et al., 2009, ApJ, 698, 1924
Patel N., Young K., Bruenken S., et al., 2009, ApJ, 692, 1205
Patel N., Young, K., Bruenken S., et al., 2009, ApJ, 691, L55

Nakashima, J., Koning N., Kwok, S., Zhang, Y., 2009, ApJ, 692, 402





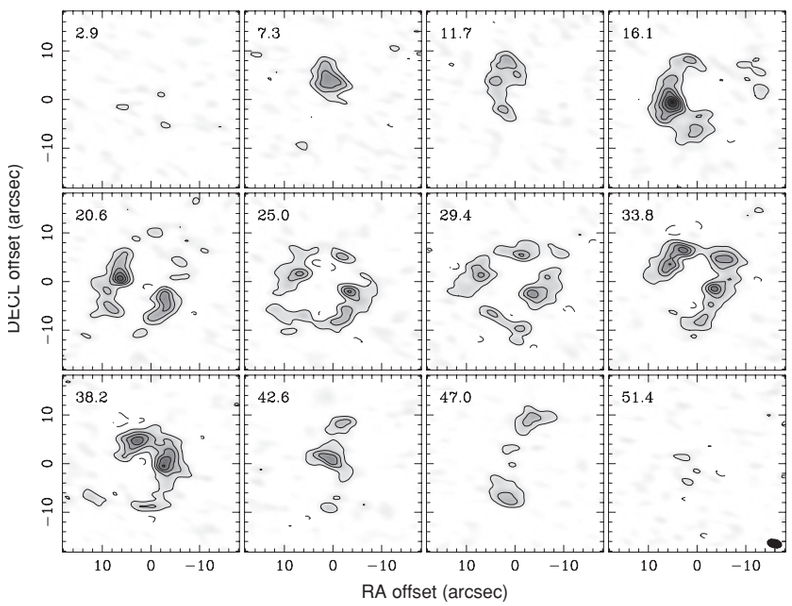


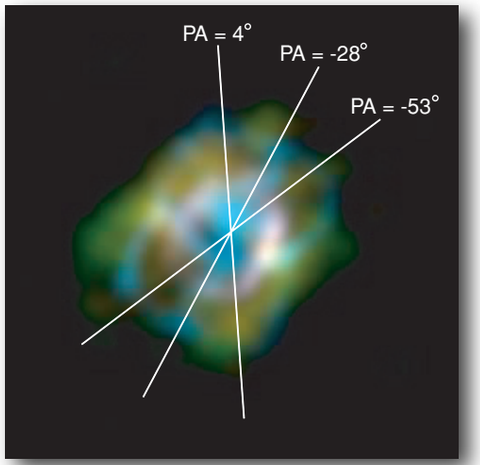


- ***Shape*** modeling
- Star left AGB ~1500 yrs ago
- Mass loss duration ~3000 yrs
- Expanding Torus 8 km s^{-1}
- No Jet: outflow may follow later

NGC 7027

SMA 6C archival

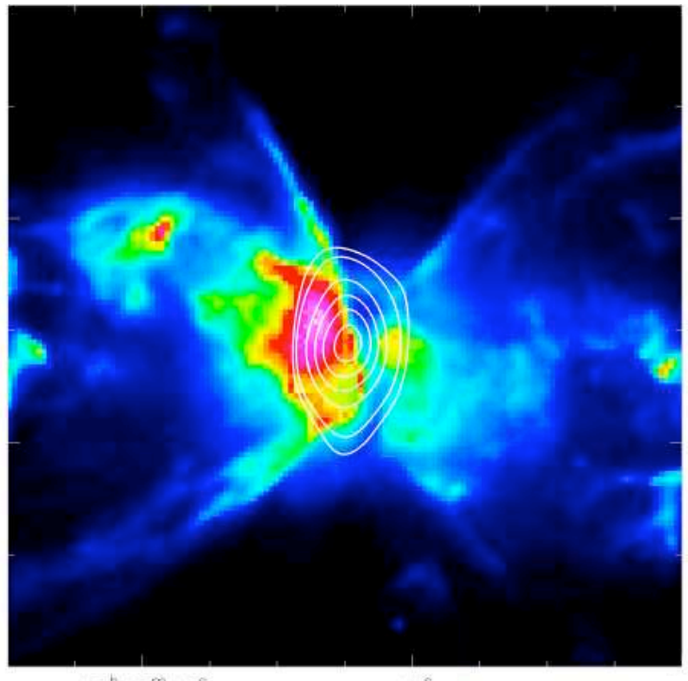


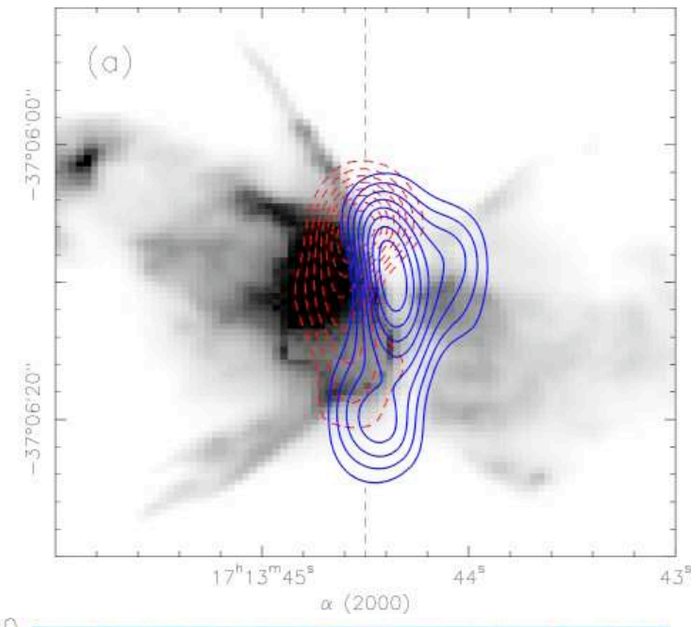


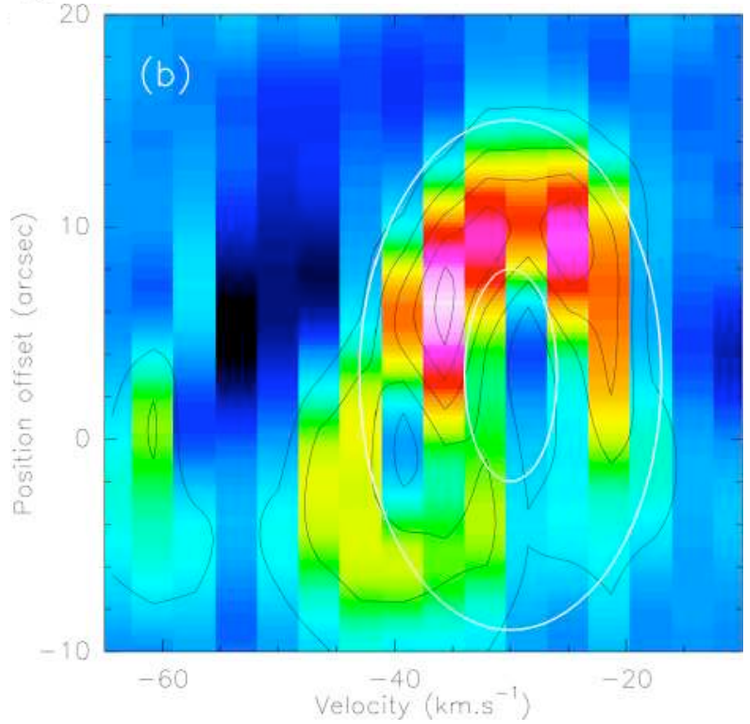
- ***Shape*** modeling
- Ellipsoidal shell model - systemic velocity
- Residual: high-velocity features
- Trail of a jet, PA=-53d, 145d
- Torus with polar regions cleared by high velocity outflow

NGC 6302 SMA 8C

Peretto N., Fuller G., Zijlstra A. & Patel N.A., 2007, A&A, 473, 207

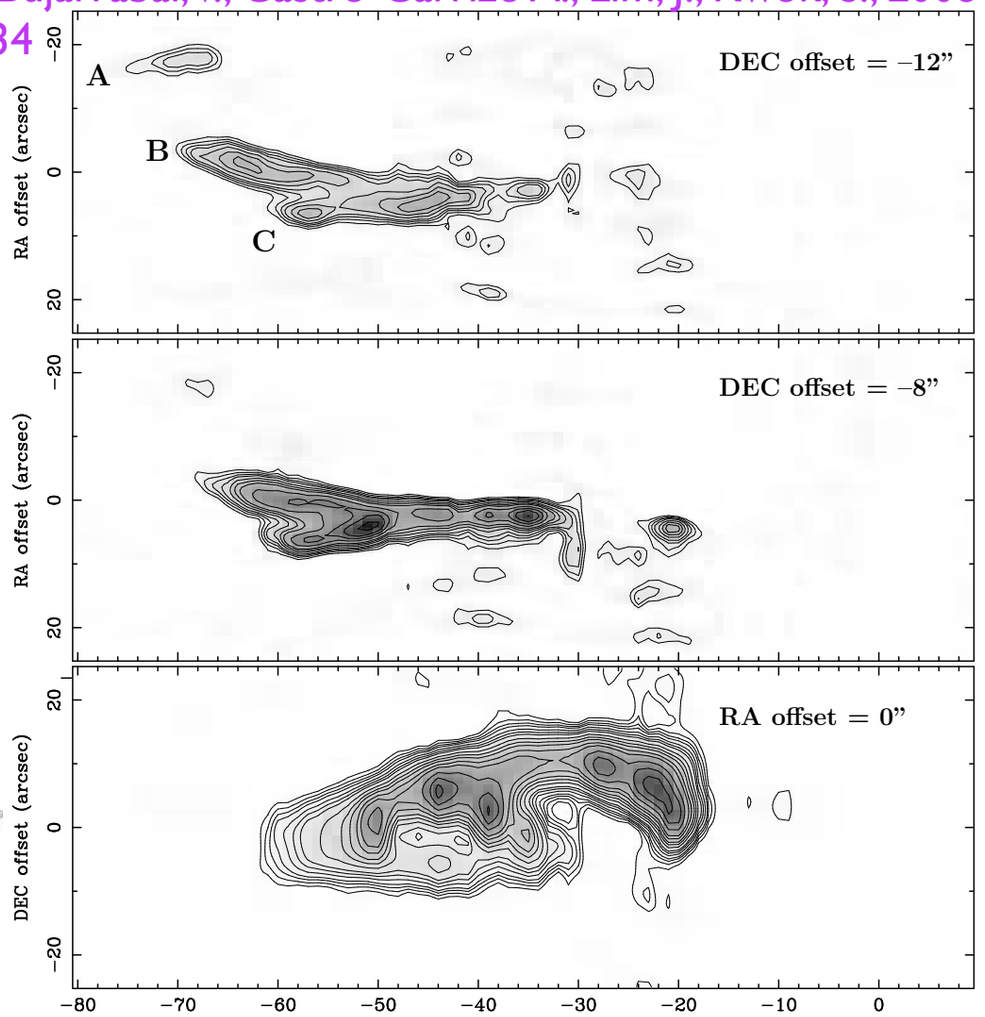


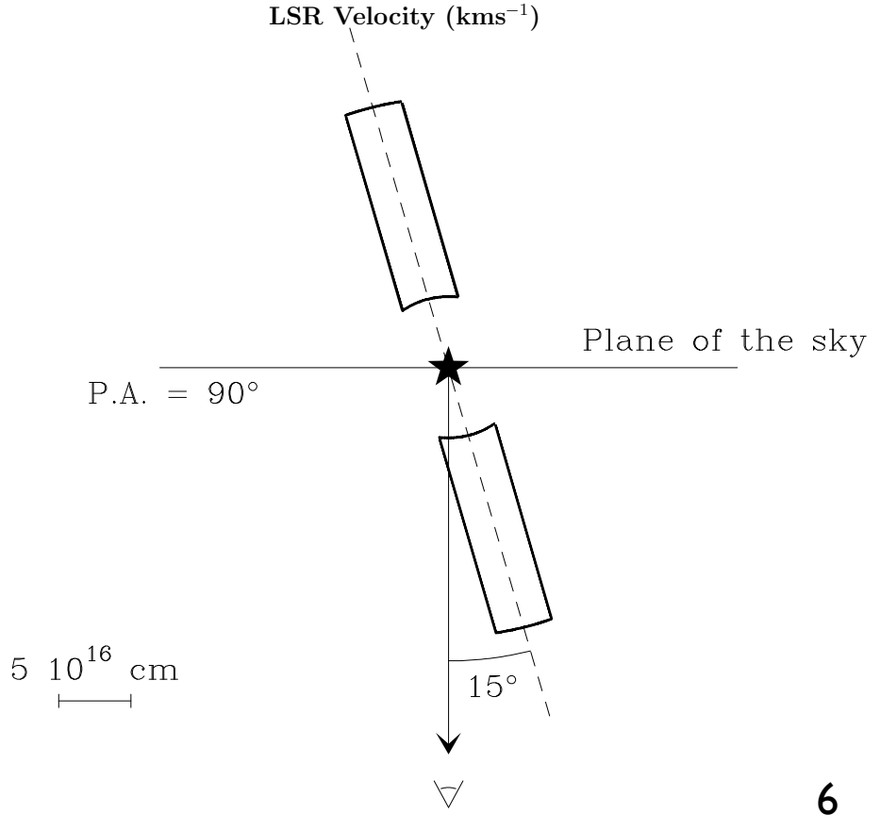




- Torus mass ~ 1.4 Msun (0.09 Msun)
- Dynamical age of torus ~7500 yrs
- Expanding Torus 8 km s^{-1} (15 km s^{-1})
- No fast CO outflow detected: terminated by ejection of inner edge of torus

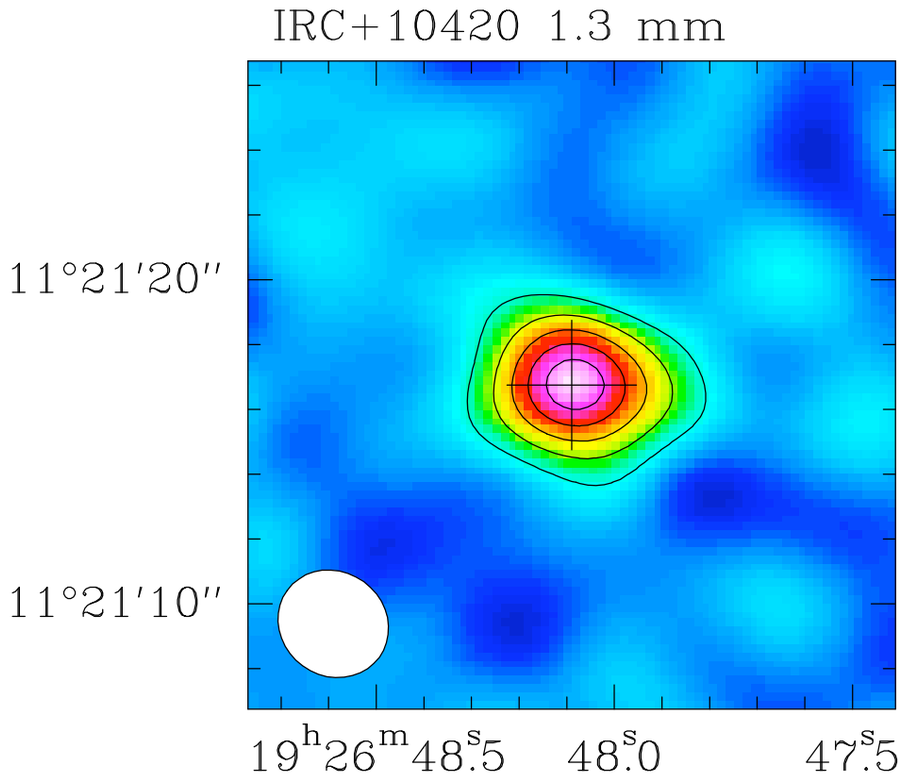
Trung, DV, Bujarrabal, V., Castro-Carrizo A., Lim, J., Kwok, S., 2008 ApJ 673, 934

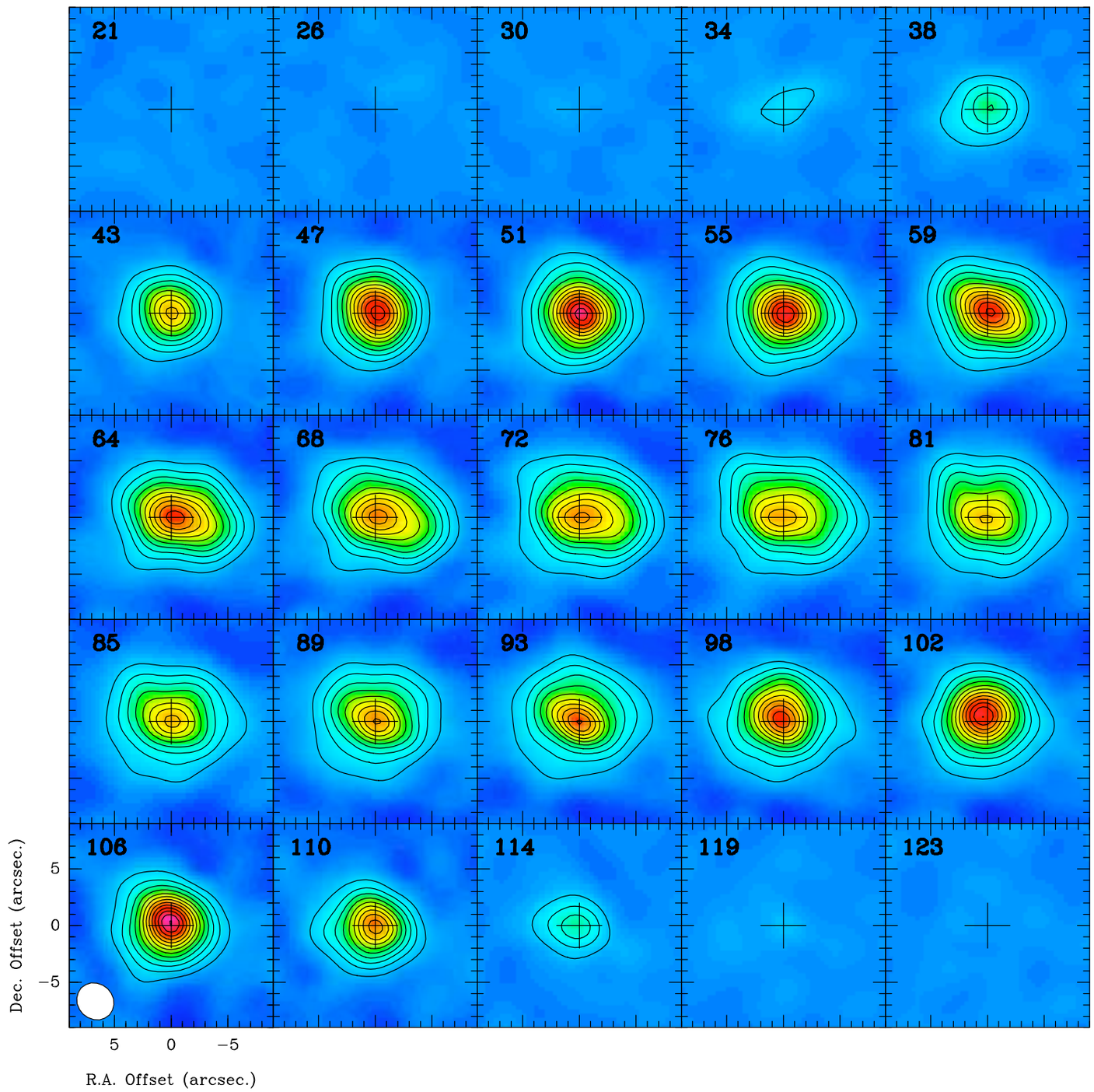




IRC+10420

SMA 8C





- Clumpy, asymmetric expanding envelope with a weak bipolar outflow
- Envelope has two concentric shells: 1”-2” and 3”-6”
- Low isotopic ratio $^{12}C/^{13}C=6$: strong mixing of processed material from stellar interior to the surface of the star

Trung, D-V, Muller, S., Lim, J., Kwok, S., Muthu, C., 2009, ApJ, 692, 409

W Hya

Muller, S., Trung, D-V, He, J., Lim, J., 2009, ApJ, 692, 409

SMA 8VEX

SMA 6VEX

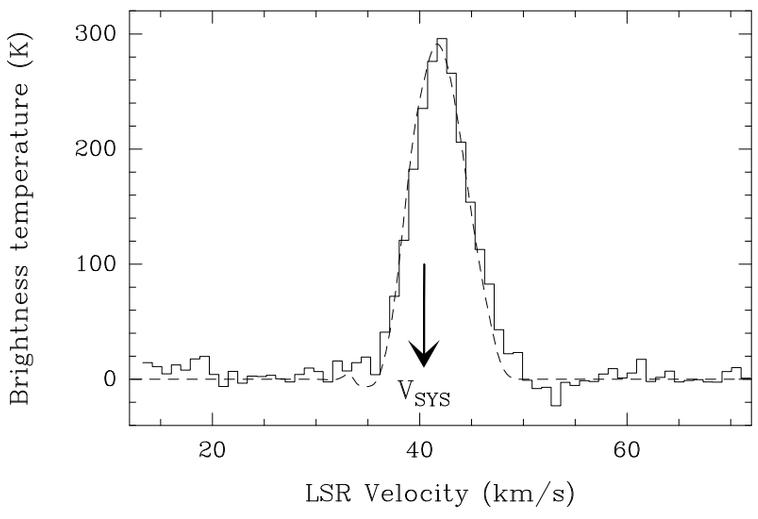
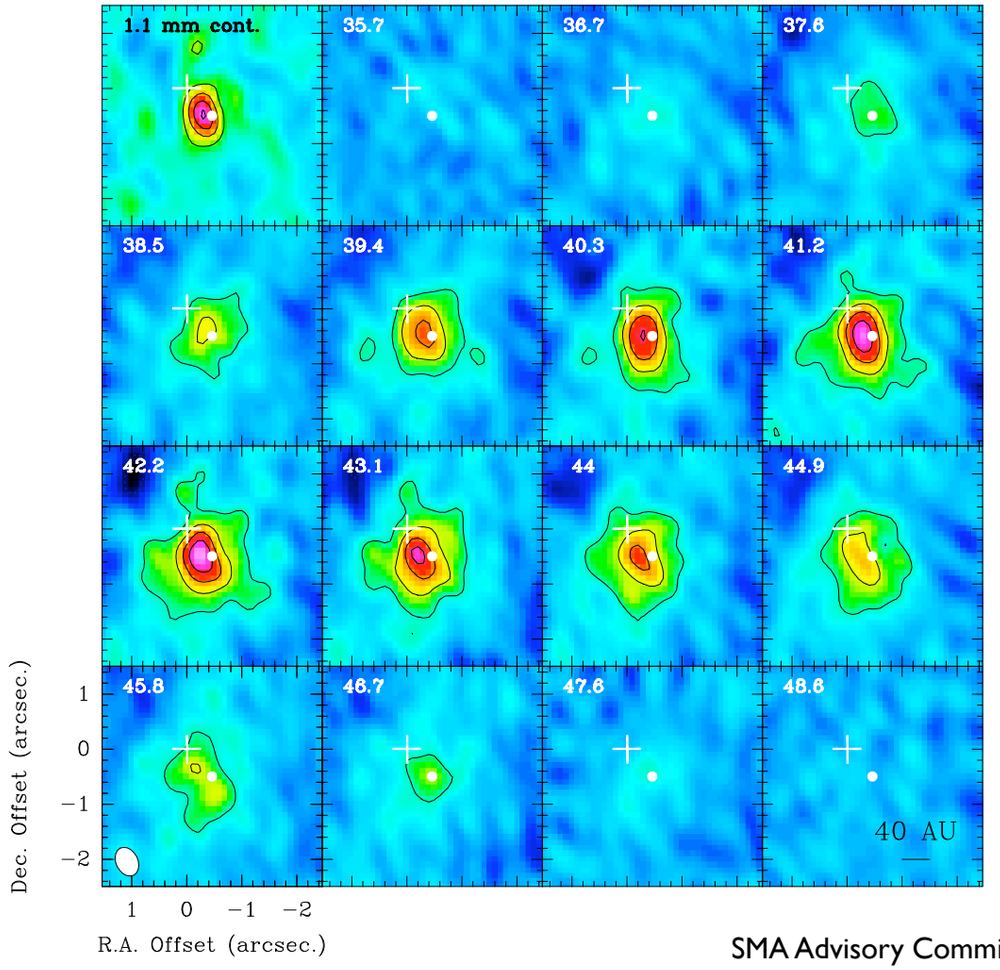
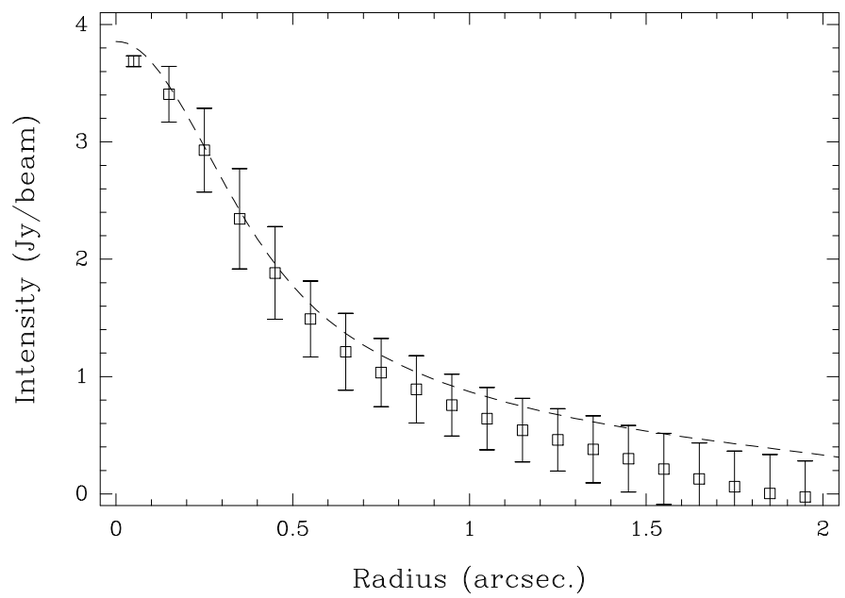


TABLE 1: MODEL PARAMETERS

	STAR	
Distance	D = 78 pc	(1)
Systemic velocity (LSR)	$V_{SYS} = 40.4$ km s^{-1}	(2)
Effective temperature	$T_{eff,\star} = 2500$ K	(3)
Stellar radius	$R_\star = 2.73 \times 10^{13}$ cm	(4)
	ENVELOPE	
Inner radius	$R_{in} = 1 \times 10^{14}$ cm	
Outer radius	$R_{out} = 3 \times 10^{15}$ cm	
Mass-loss rate	$\dot{M} = 5 \times 10^{-7}$ $M_\odot$ yr^{-1}	
Temperature profile	$T(r) = 650$ K $(r/R_{in})^{-1}$	
Launching velocity	$V_0 = 2$ km s^{-1}	(5)
Terminal velocity	$V_\infty = 7$ km s^{-1}	(4)
Velocity law ($r < R_{out}$)	$V(r) = \frac{(V_\infty - V_0)\log_{10}(r/R_{in})}{\log_{10}(10^{16}\ \mathrm{cm}/R_{in})} + V_0$	
Abundance of HCN	$[HCN]/[H_2] = 10^{-6}$	
Local turbulent velocity	$\sigma_{turb} = 1$ km s^{-1}	

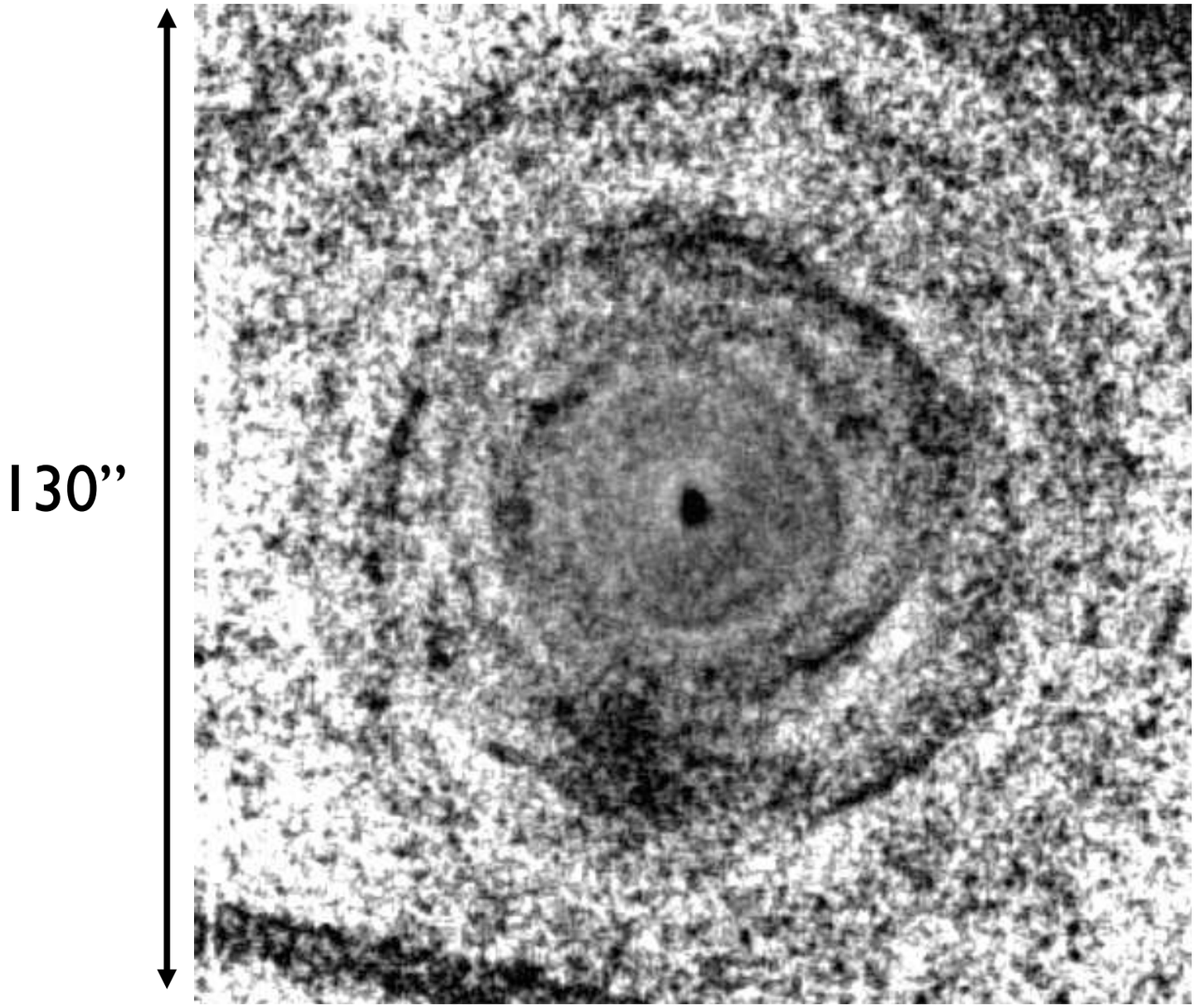
REFERENCES. — (1) Knapp et al. (2003); (2) Cernicharo et al. (1997); (3) Haniff et al. (1995); (4) Justtanont et al. (2005); (5) Miyoshi et al. (1994).



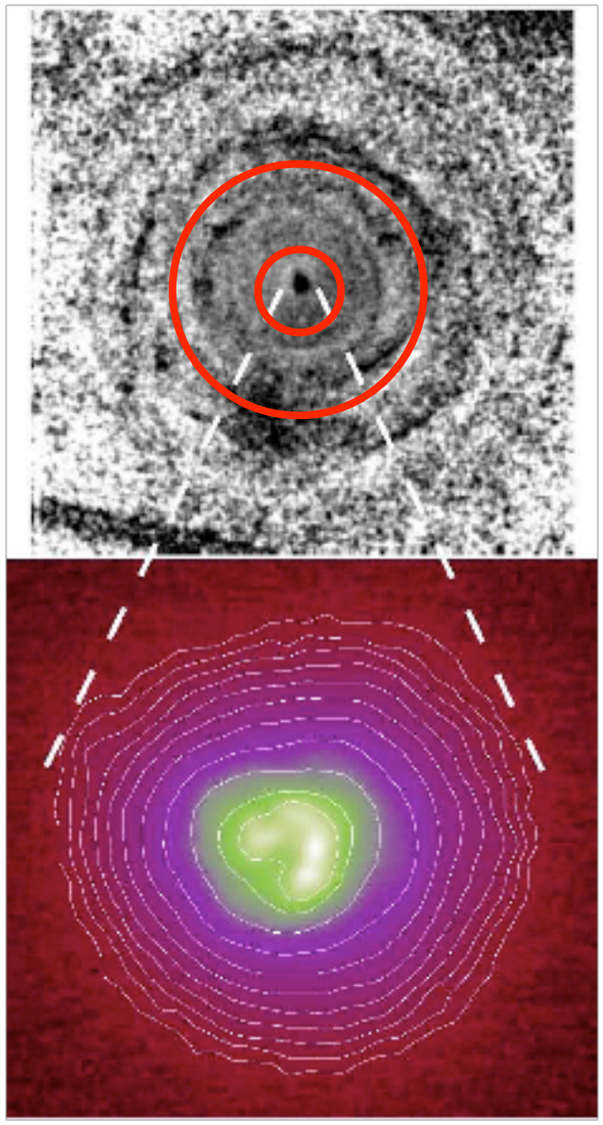


IRC+10216 (CW Leo)

- Nearest and brightest Carbon-rich AGB star (distance: ~150 pc)
- Mass loss rate = several x 10^{-5} Msun/yr

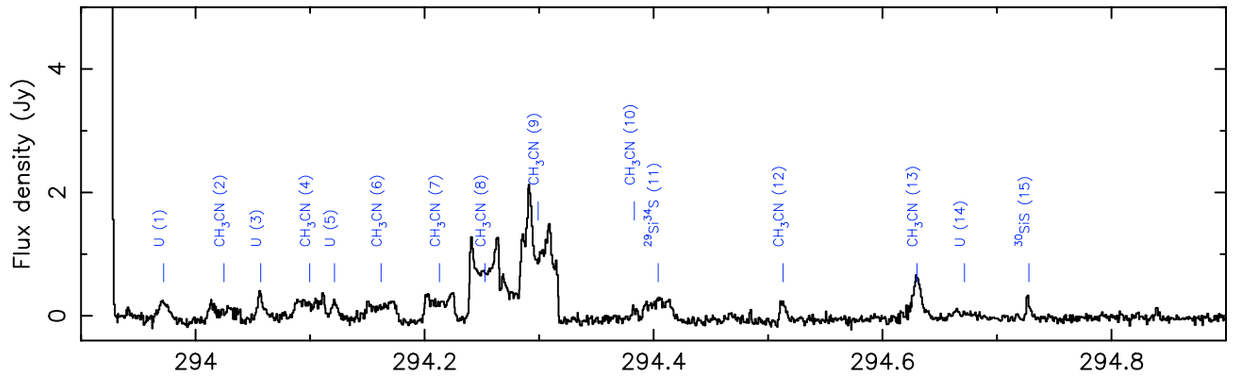


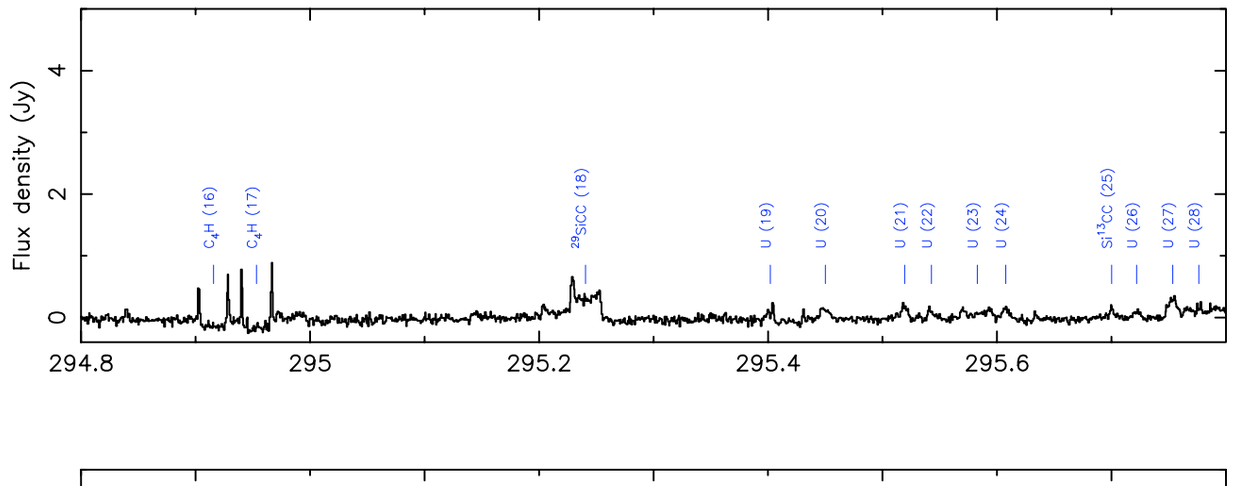
VLT - AO

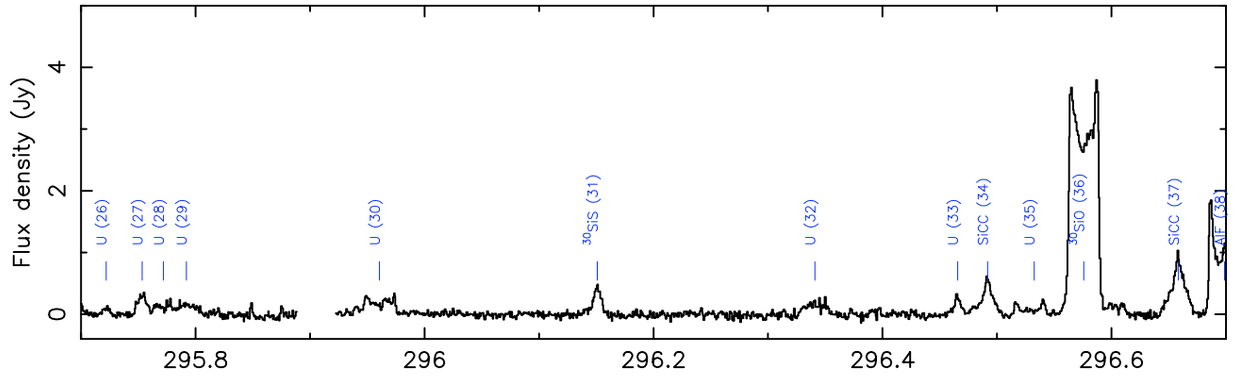


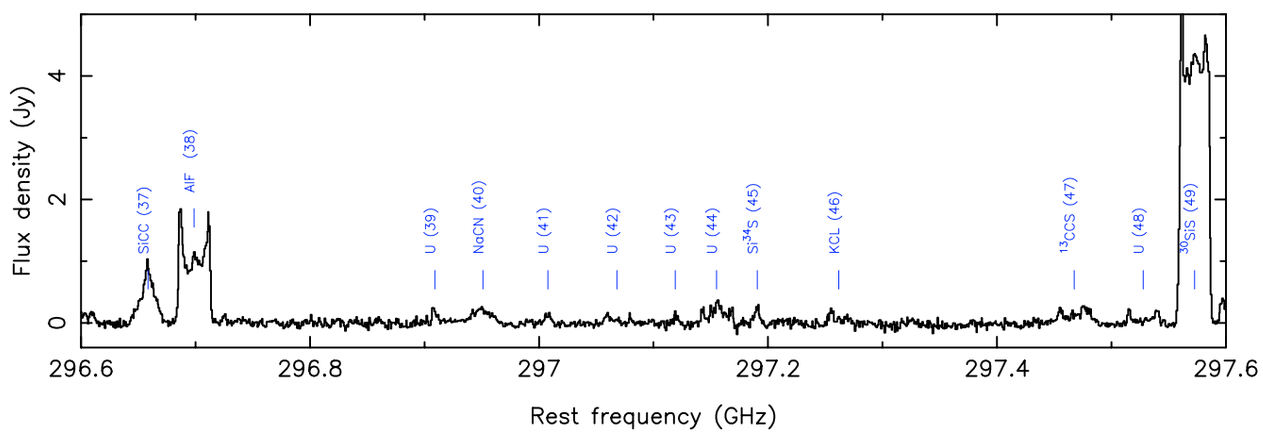
130”

2”

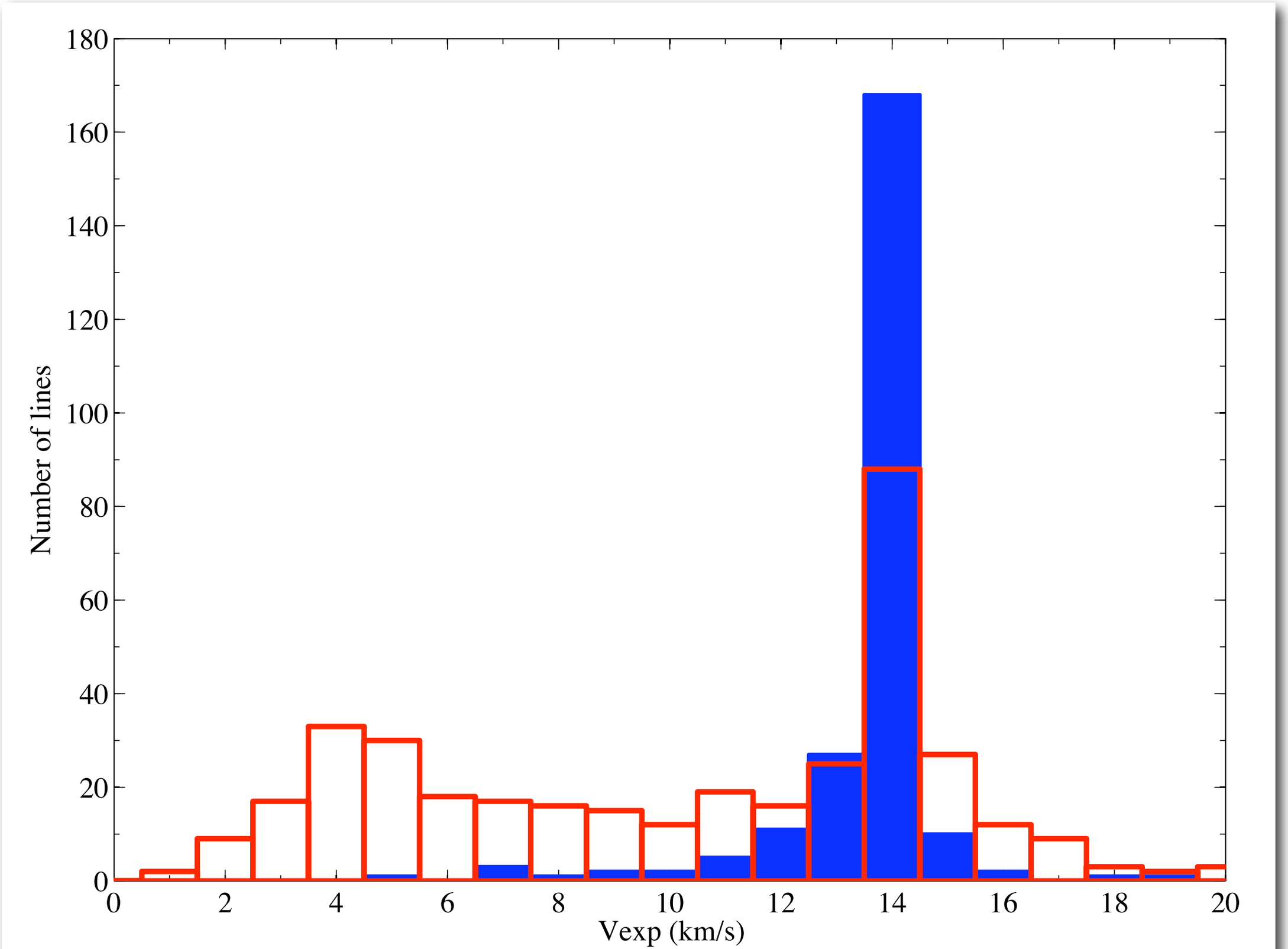

Flux density (Jy)
0
2
4
294
294.2
294.4
294.6
294.8
U (1)
CH3CN (2)
U (3)
CH3CN (4)
U (5)
CH3CN (6)
CH3CN (7)
CH3CN (8)
CH3CN (9)
CH3CN (10)
29Si34S (11)
CH3CN (12)
CH3CN (13)
U (14)
30SiS (15)


Flux density (Jy)
0
2
4
294.8
295
295.2
295.4
295.6
C4H (16)
C4H (17)
29SiCC (18)
U (19)
U (20)
U (21)
U (22)
U (23)
U (24)
Si13CC (25)
U (26)
U (27)
U (28)


Flux density (Jy)
0
2
4
295.8
296
296.2
296.4
296.6
U (26)
U (27)
U (28)
U (29)
U (30)
30SiS (31)
U (32)
U (33)
SiCC (34)
U (35)
30SiO (36)
SiCC (37)
AlF (38)

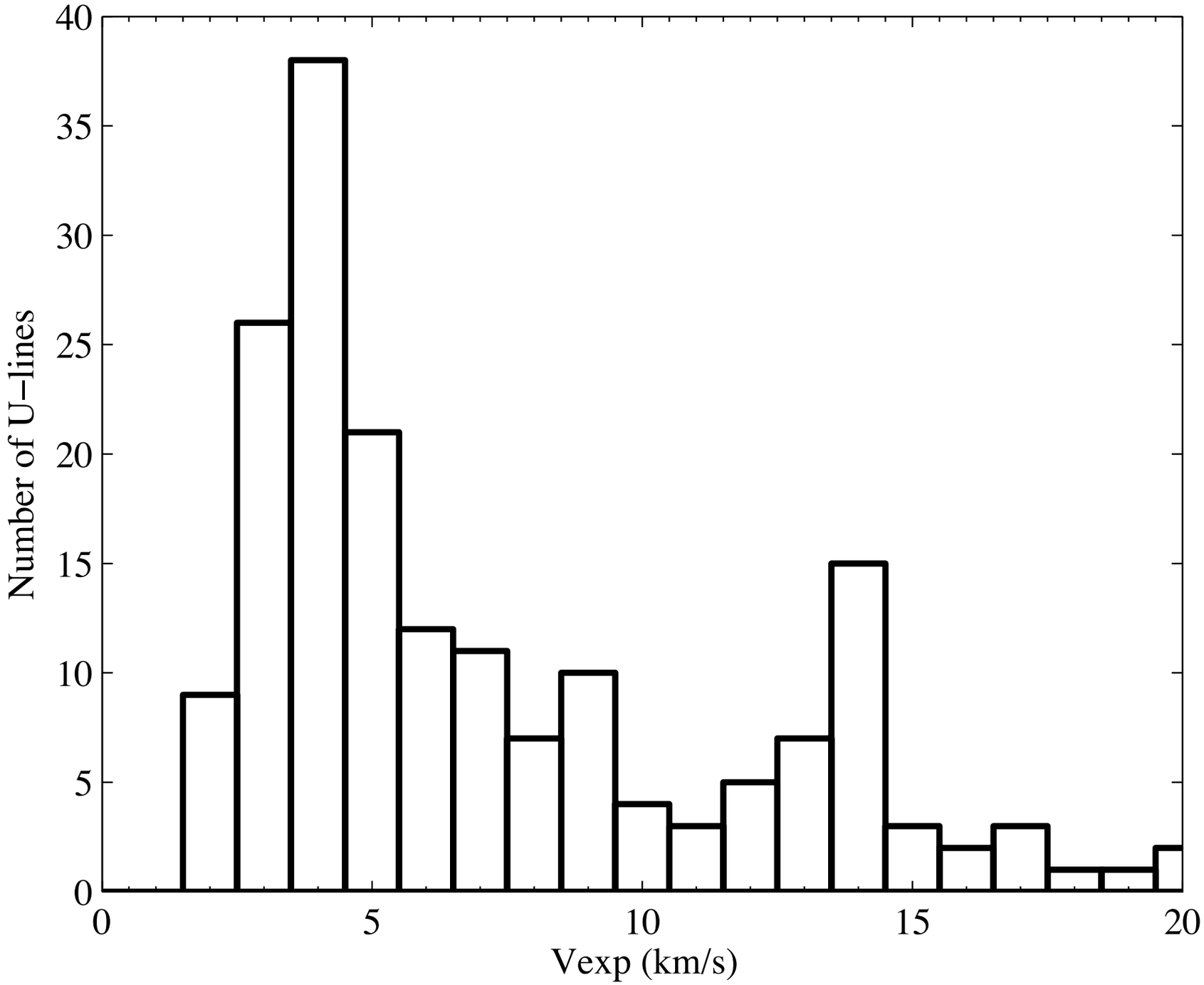

Flux density (Jy)
0
2
4
296.6
296.8
297
297.2
297.4
297.6
Rest frequency (GHz)
SiCC (37)
AlF (38)
U (39)
NaCN (40)
U (41)
U (42)
U (43)
U (44)
Si34S (45)
KCL (46)
13CCS (47)
U (48)
30SiS (49)

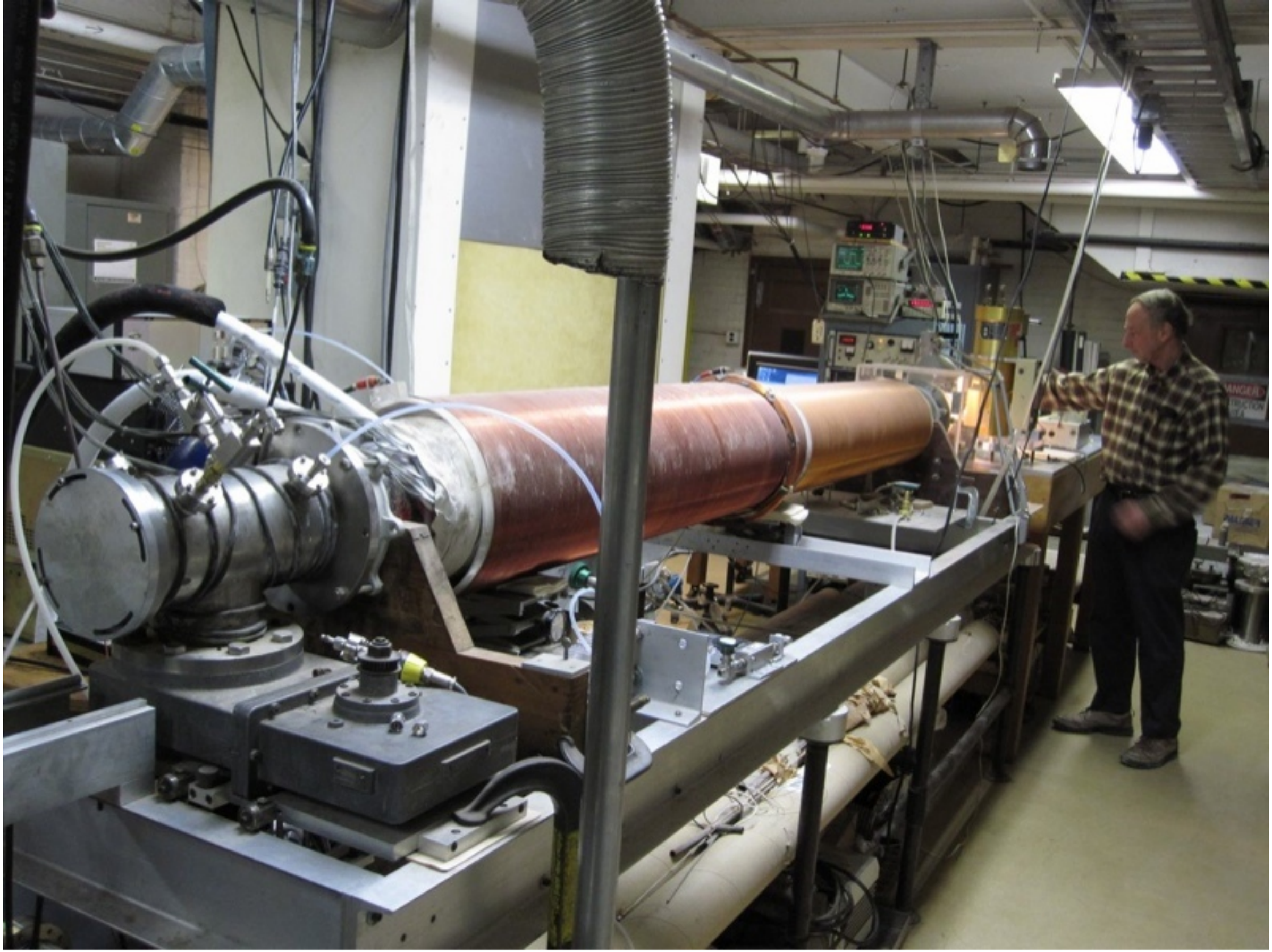
New population of narrow lines

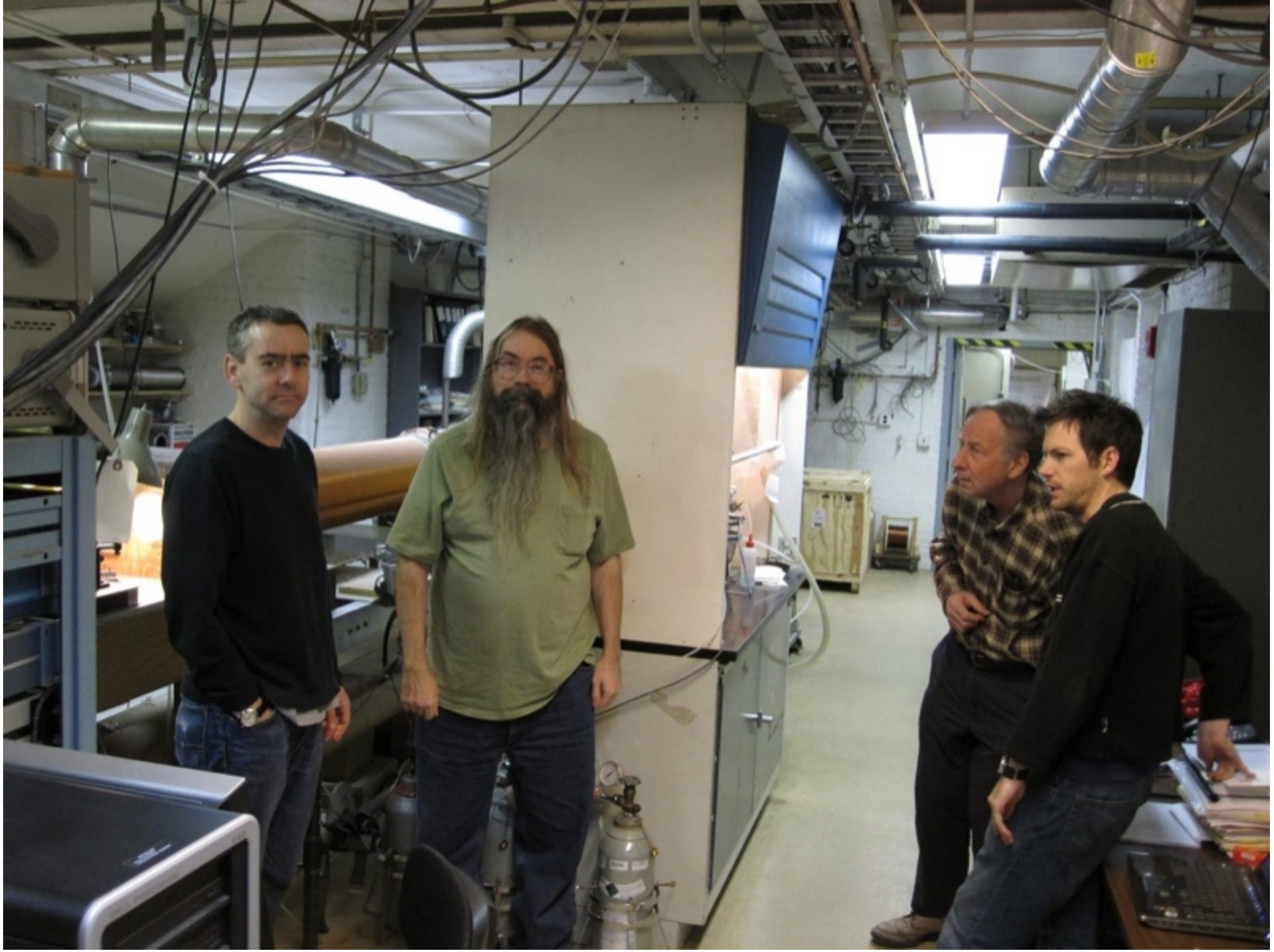


Distribution of expansion velocities of U-lines

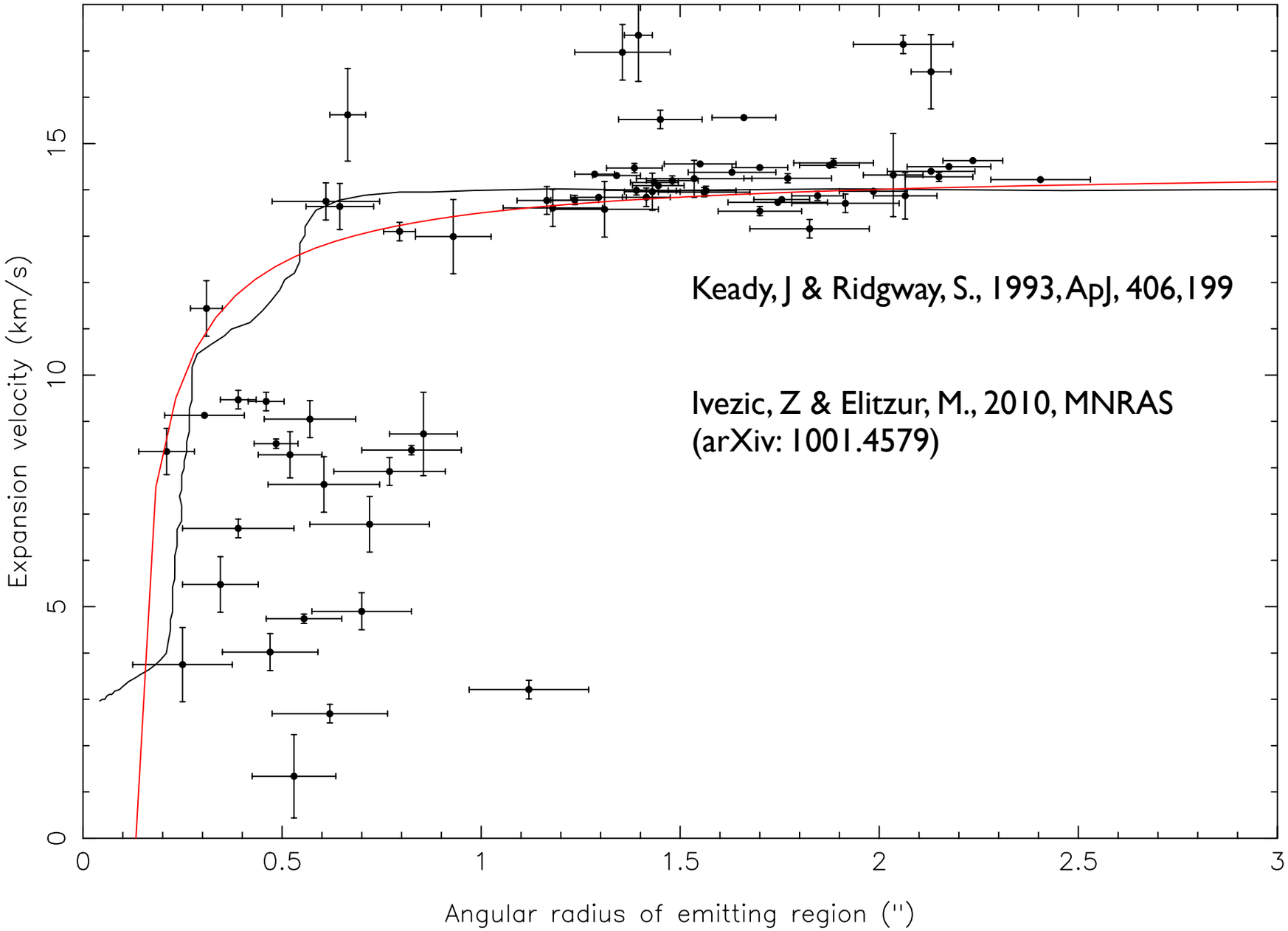
(most U-lines are narrow)

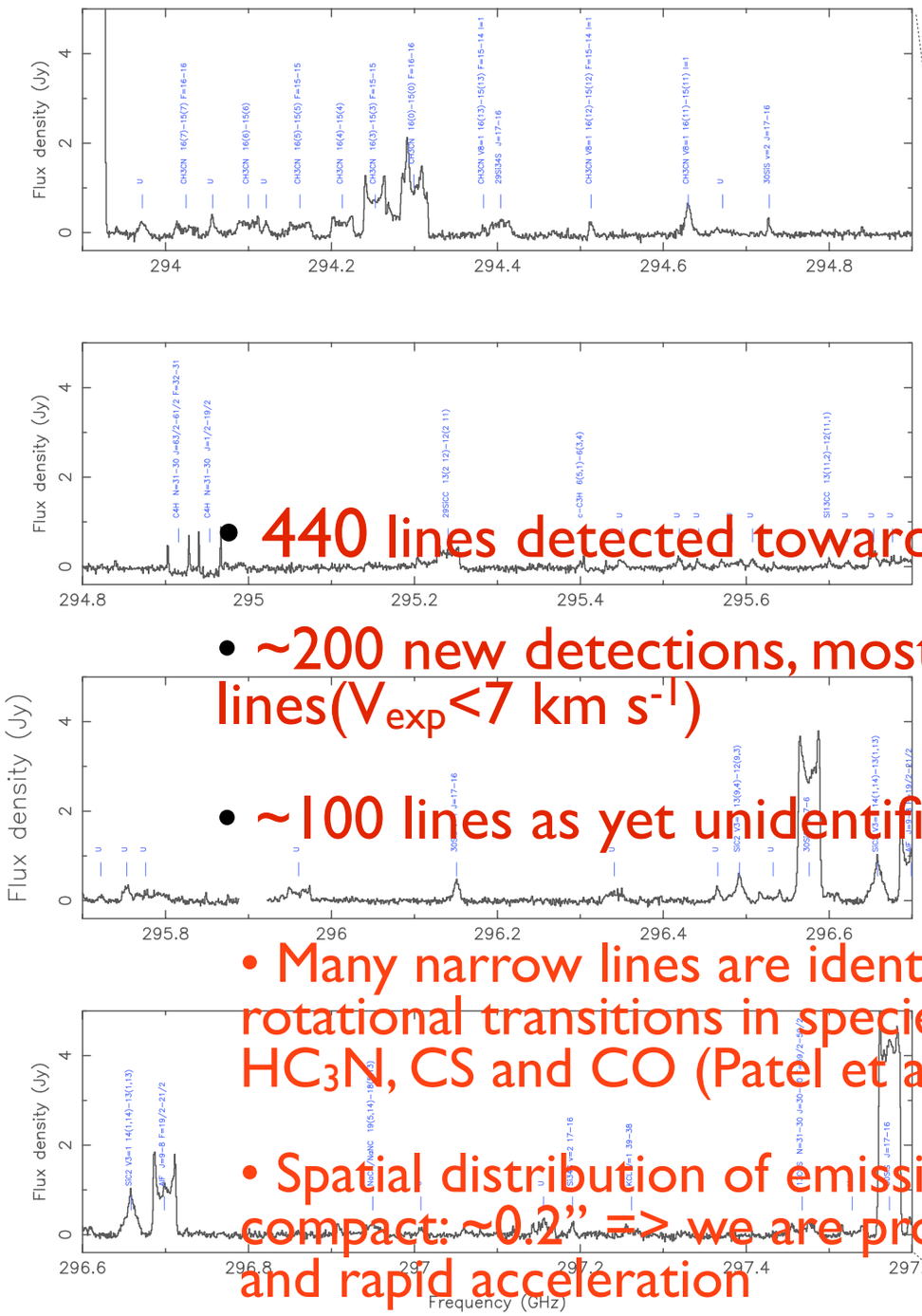


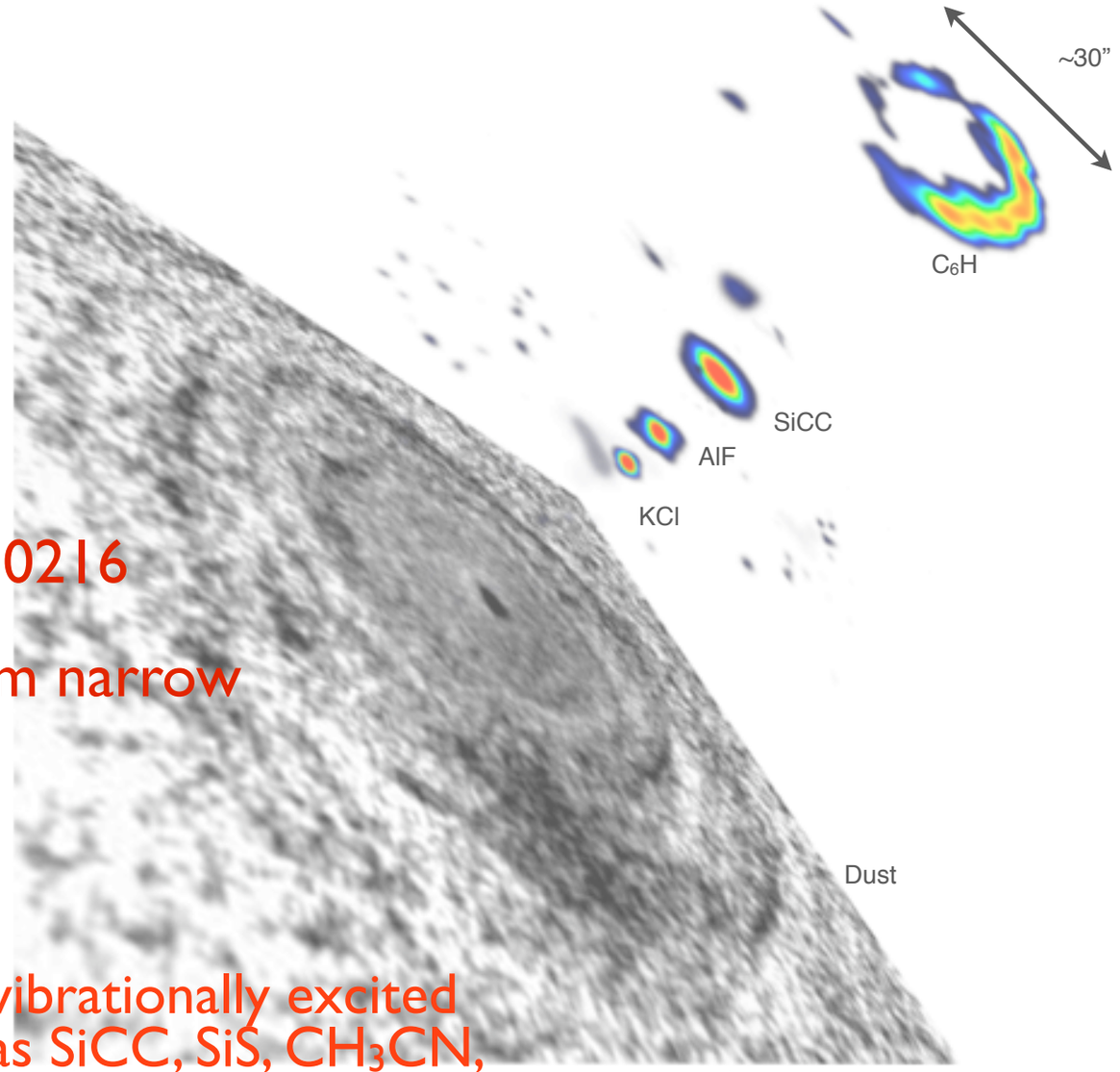


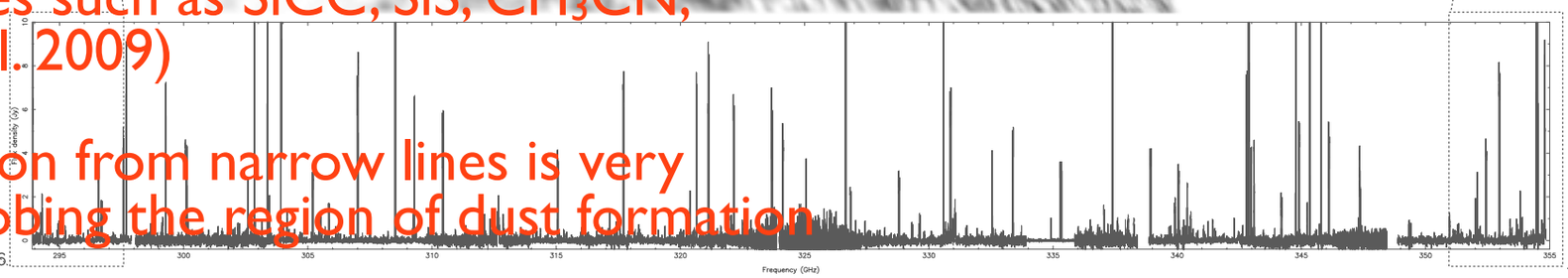


Expansion velocity profile





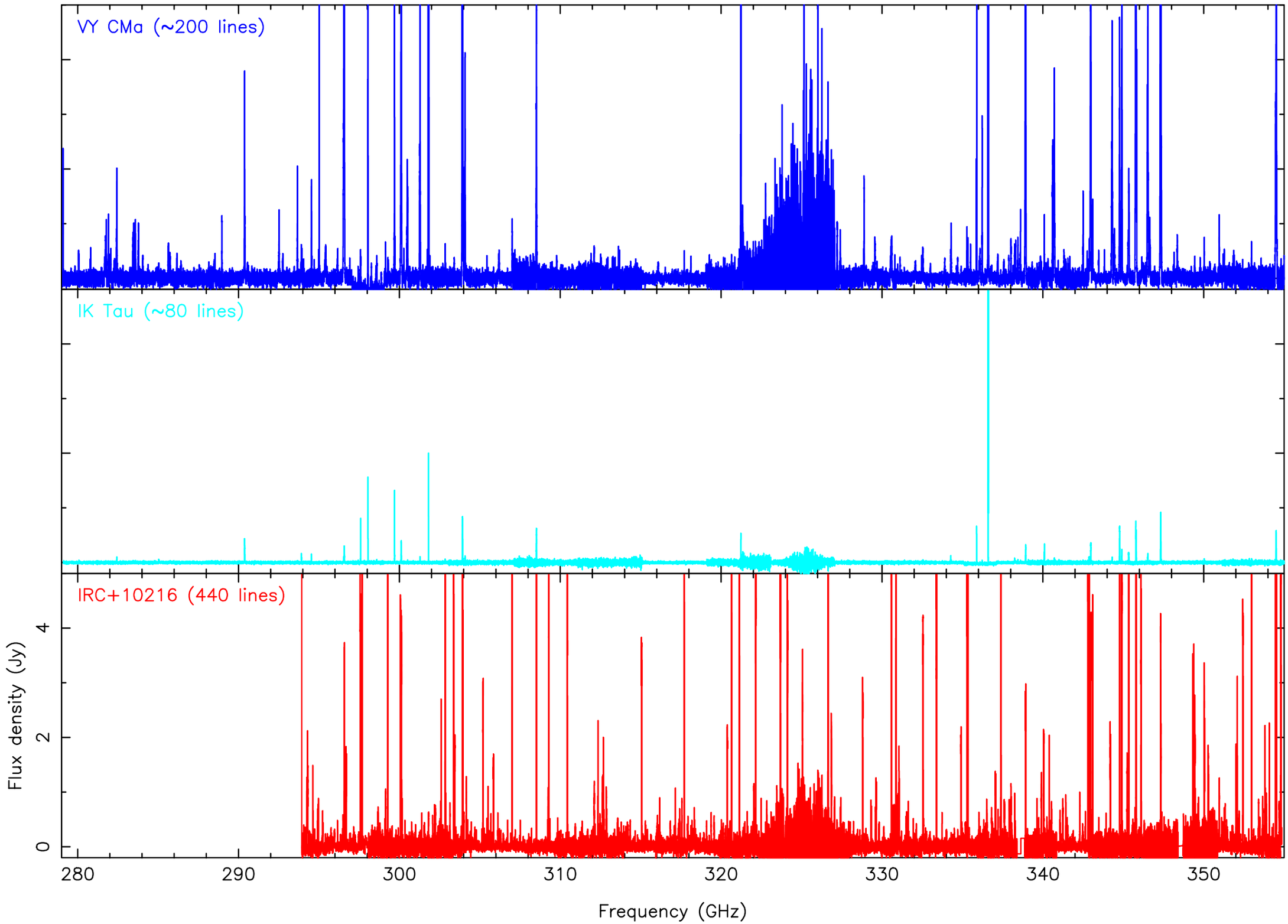




- 440 lines detected toward IRC+10216
- ~200 new detections, most of them narrow lines(V_{exp}<7 km s^{-1})
- ~100 lines as yet unidentified
- Many narrow lines are identified as vibrationally excited rotational transitions in species such as SiCC, SiS, CH_3CN, HC_3N, CS and CO (Patel et al. 2009)
- Spatial distribution of emission from narrow lines is very compact: ~0.2” => we are probing the region of dust formation and rapid acceleration
- Images and calibrated visibility data-sets of full survey will be made publicly available on acceptance of ApJSS paper.
- Recently completed SMA line-surveys: VY CMa, IK Tau (O-rich AGB stars; PI: Ken Young)

Line surveys of VY CMa and IK Tau

Young et al. 2010



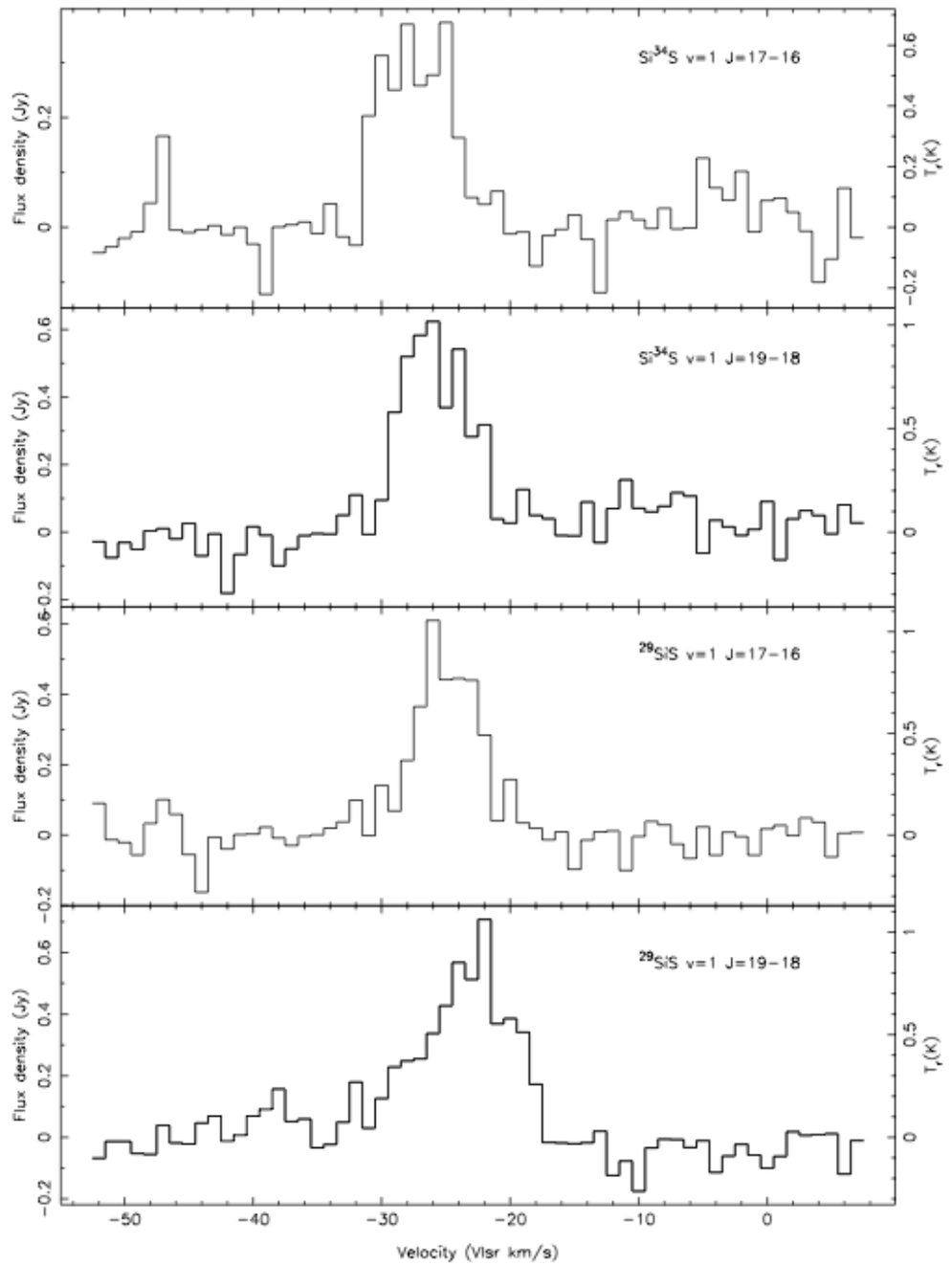
Detection of narrow lines in IRC+10216

$Si^{34}S$ v=1, J=17-16
298.63 GHz

$Si^{34}S$ v=1, J=19-18
333.73 GHz

^{29}SiS v=1, J=17-16
301.39 GHz

^{29}SiS v=1, J=19-18
336.82 GHz



E_u/K~1200 K

Isotopic abundance ratios ~ solar values

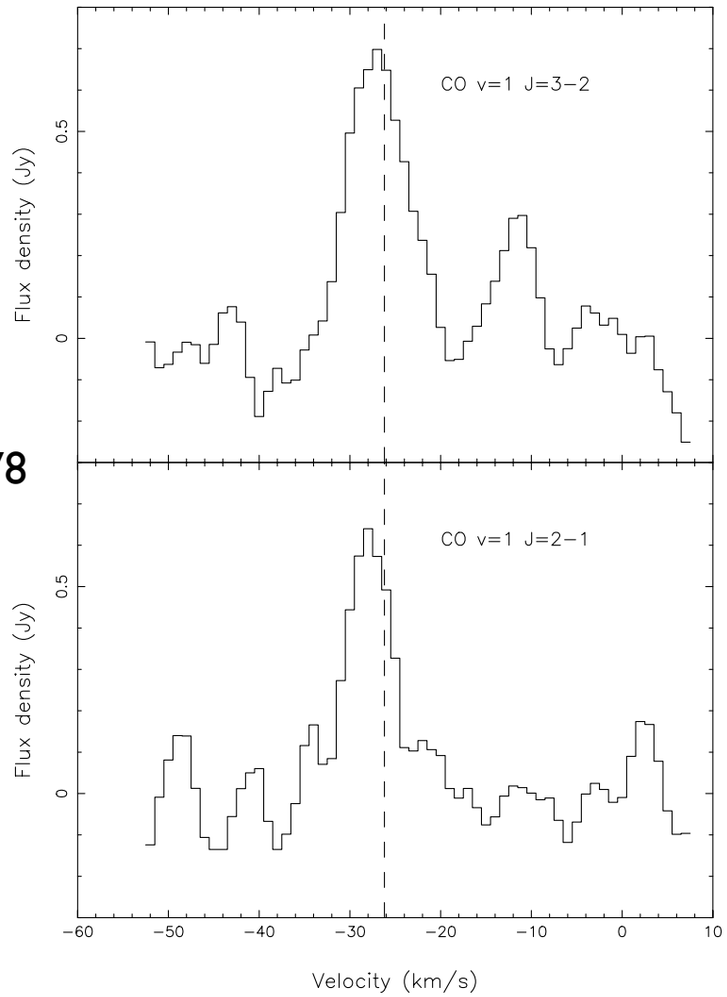
Patel, Young, Brünken et al. (2009) ApJ 692,1205

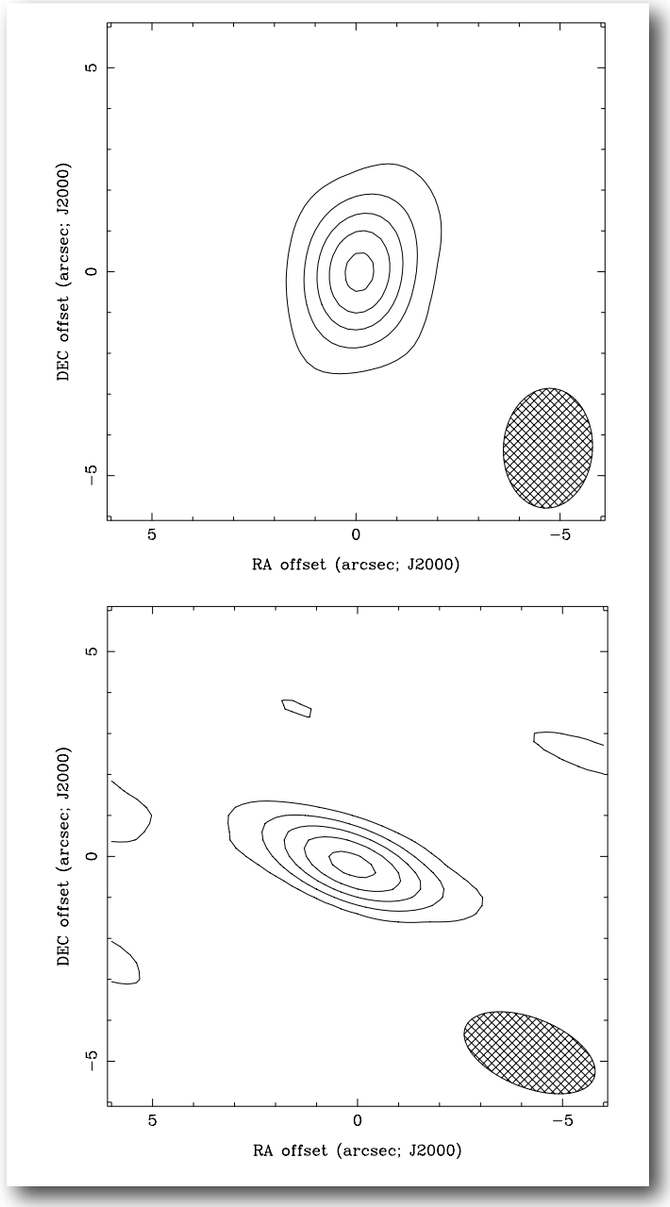
First astronomical detection of vibrationally excited CO emission

CO v=1 J=3-2 342.65 GHz,
J=2-1 228.44 GHz

E_u/K=3116 K

Previous attempt to detect v=1 J=1-0 line:
Scoville, K & Solomon, P., 1978
Cummins et al. 1980



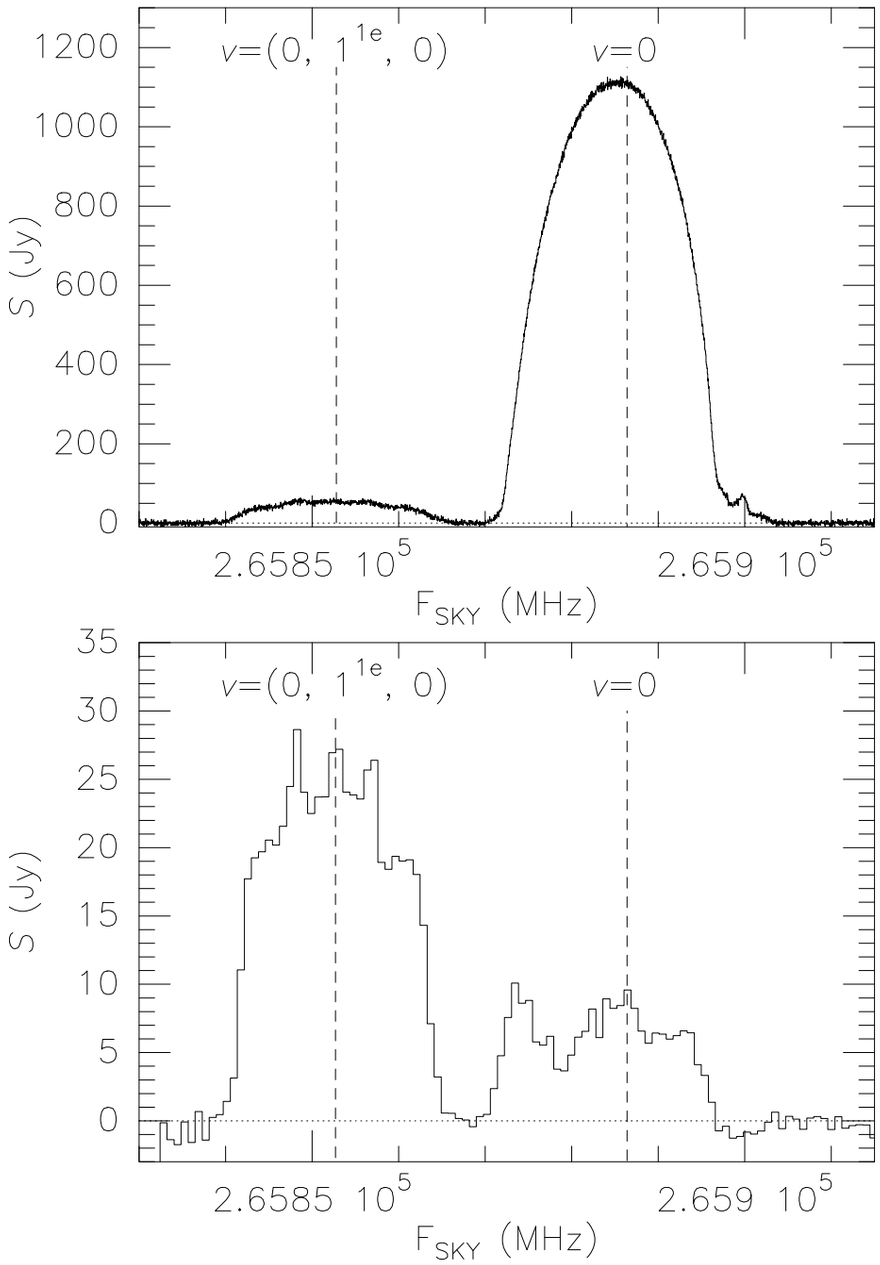


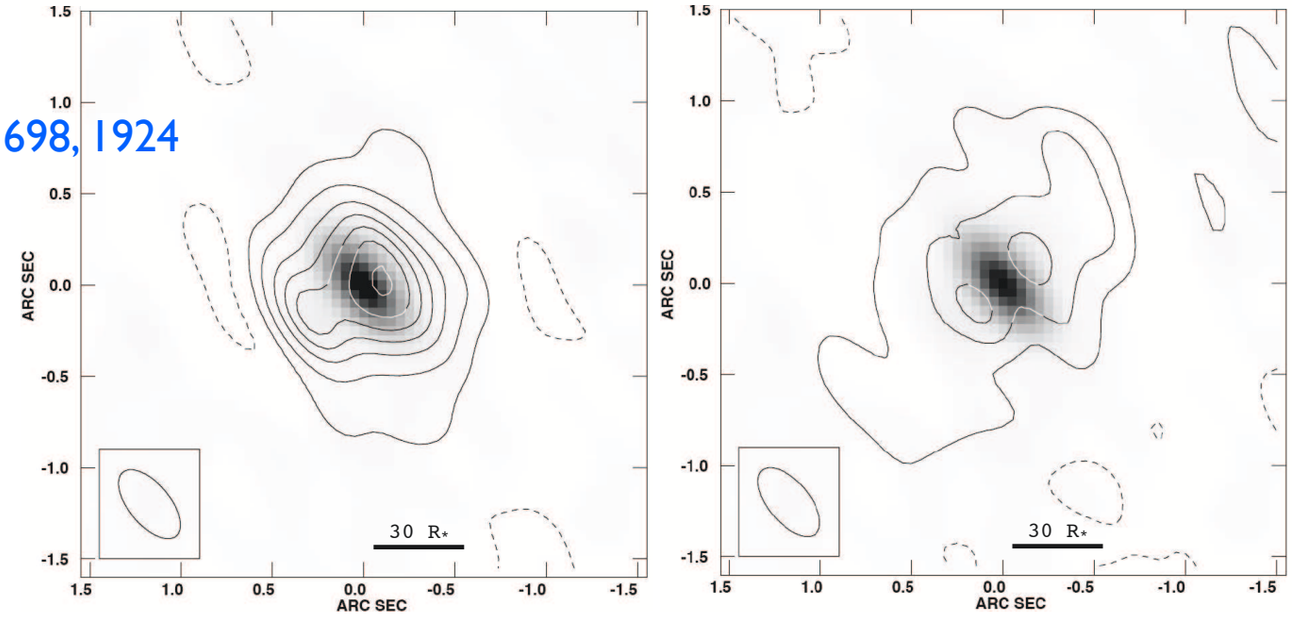
CS and CO v=1 likely to be radiatively excited

Patel, Young, Brünken et al. (2009) ApJ 691,L55

eSMA observations of IRC+10216

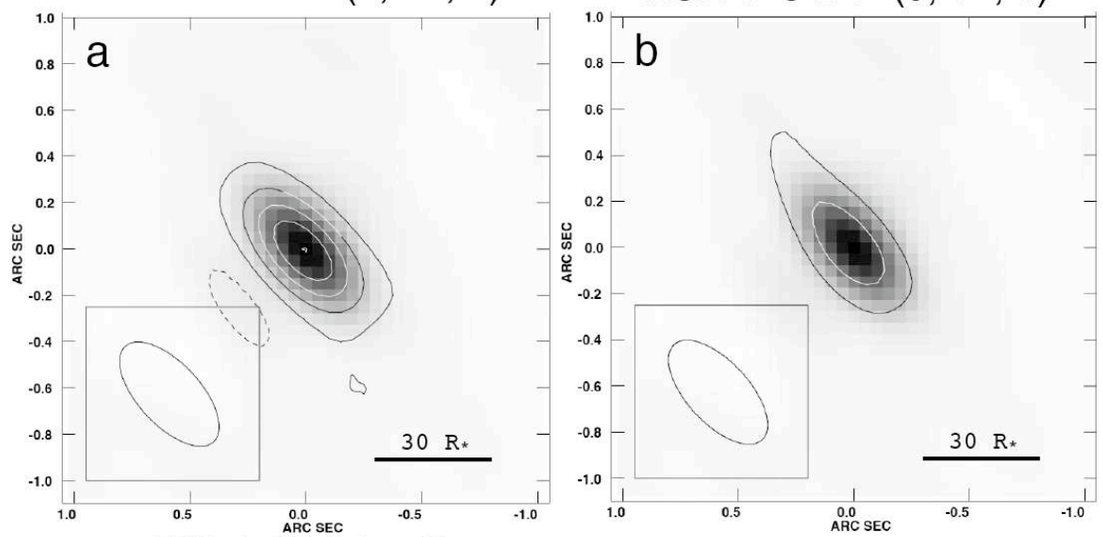
Shinnaga, H., Young, K., Tilanus, R., Chamberlin, R, et al., 2009, ApJ, 698, 1924





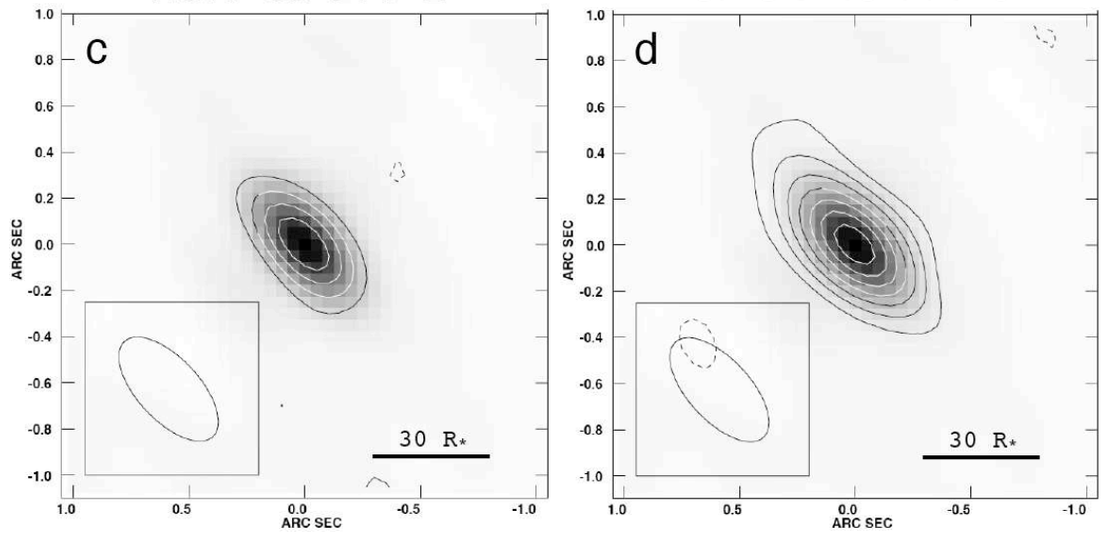
HCN J=3-2 v=(1, 1^{1f}, 0)

HCN J=3-2 v=(0, 1^{1f}, 1)



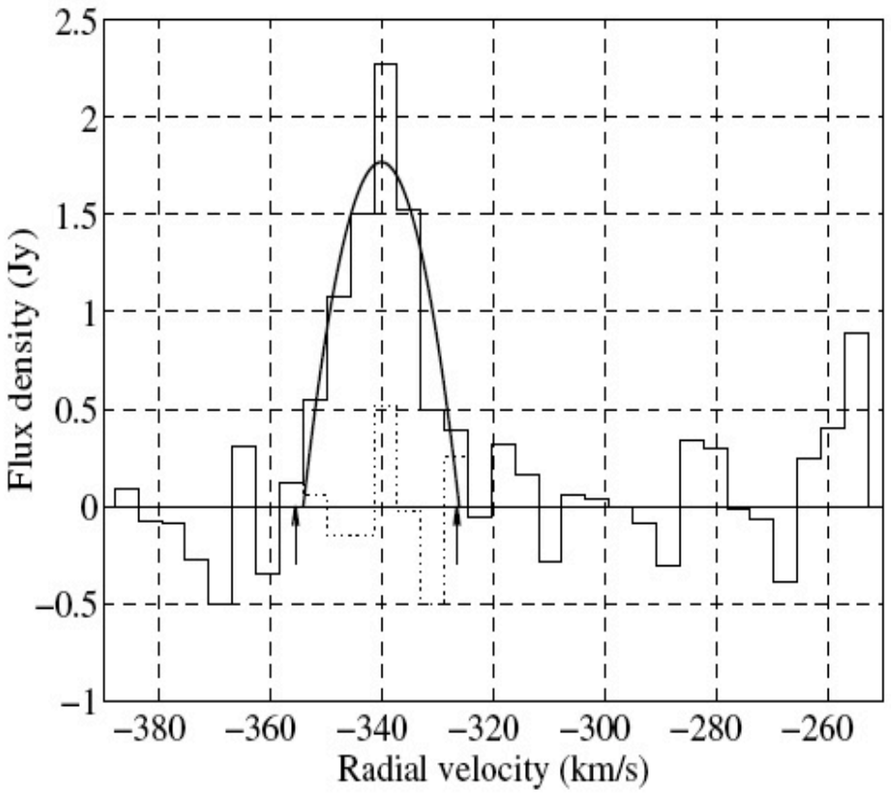
KCl J=35-34 v=2

Si^{34}S J=15-14 v=0

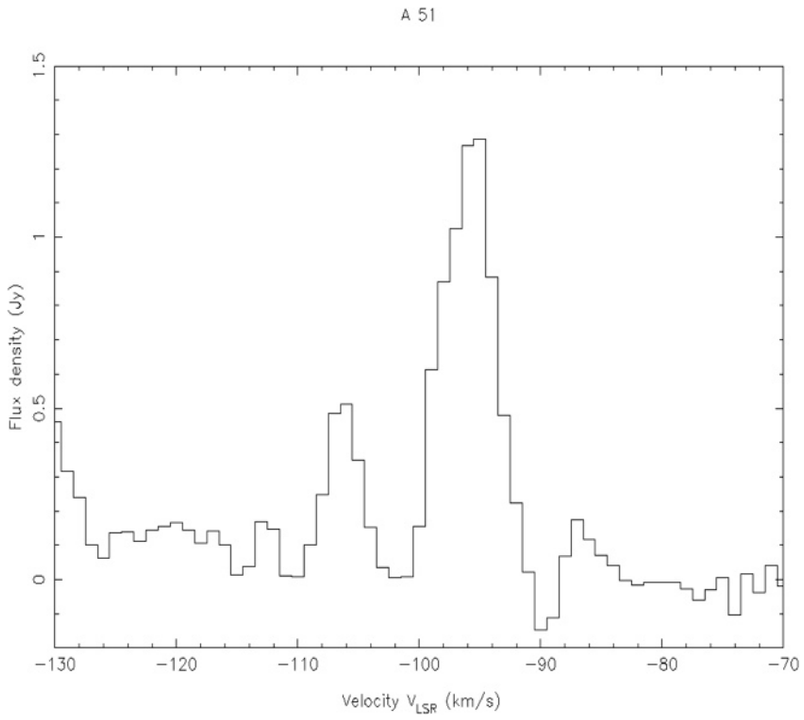


Detection of CO emission in Galactic bulge AGB stars:

Winnberg et al. (2009)



Schulteis name	Comment	line flux (JyXkm/s)	Mdot
A12	detected	42.5	8.3x10^-4
A51	detected	32	6.24x10^-4
A10	confused	...	?
A27	3 potential	...	?



OH 359.681-0.095