FISSS — 17 May 2011

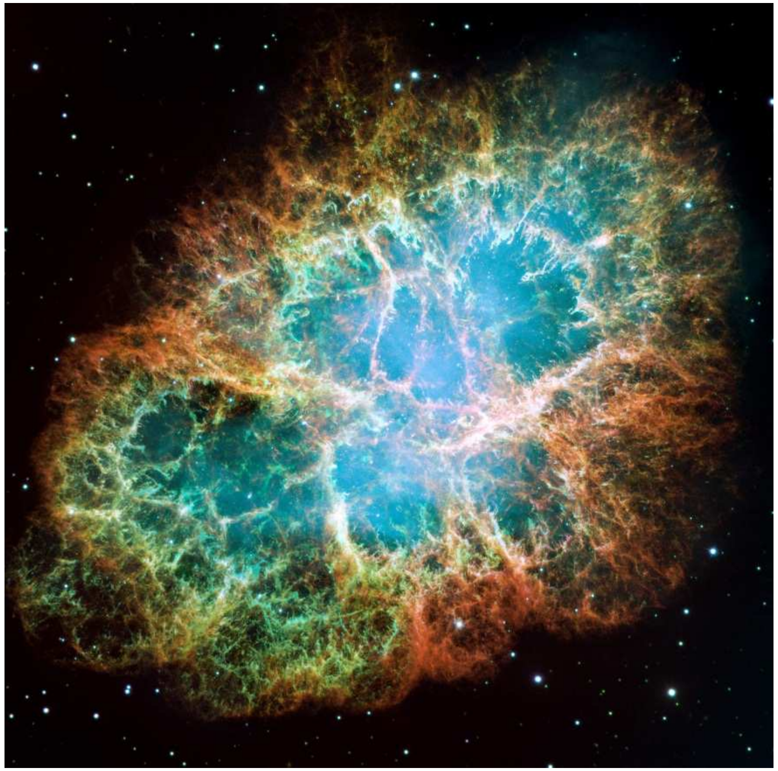
SOAR-Spartan survey of molecular hydrogen in the Crab Nebula

Ed Loh[1], J Baldwin[1], G Ferland[2], Z Curtis[1], C R O'Dell[3], A Fabian[4], & P Salomé[5]
[1]Michigan State U, [2]U Kentucky, [3]Vanderbilt U, [4]U Cambridge, [5]Obs Paris

- Outline
  - Why Crab is interesting
  - Observations
  - Velocities & spatial distribution
  - Temperature
  - Ortho:para ratio
  - Mass
- Papers
  - A bright molecular core in a Crab filament, 2010 ApJ 716, L9
  - A survey of molecular hydrogen in the Crab Nebula, ApJ, 2011arXiv1103.6043L
  - The H2 temperature in the Crab Nebula, submitted.

Survey of H_2 in the Crab Nebula

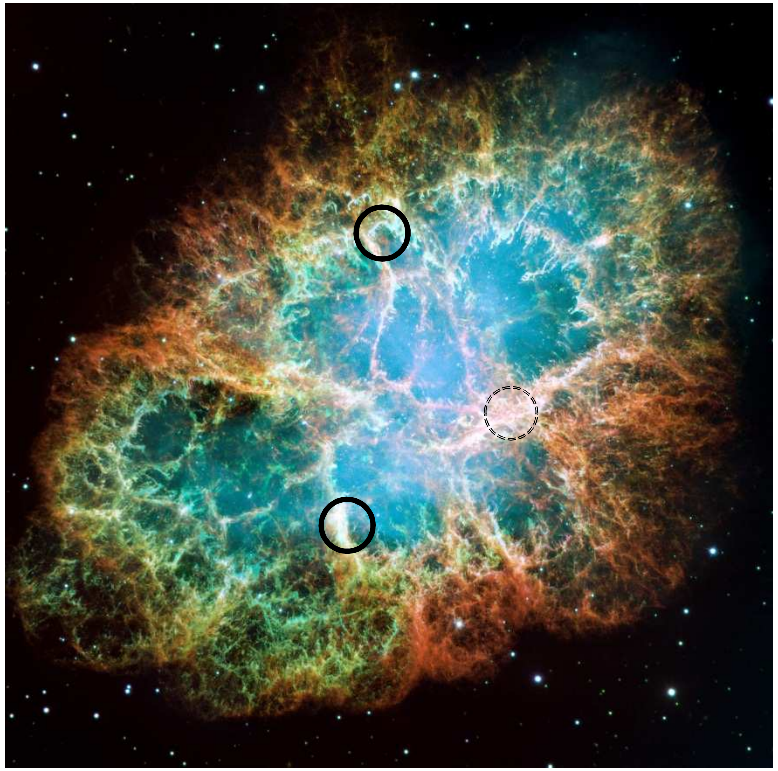
- The Crab Nebula is a unique object
  - It is close. 1arcsec = 3×10^{16}cm = 10LightDay = 2000AU
  - Young. Supernova of 1054CE
  - Pulsar makes a wind of electrons & positrons.
    - 10TeV at the H_2 knots.
  - Bright synchrotron radiation.
    - Constant νL_ν (erg/s) from far IR to 1MeV γ



NASA, ESA, J. Hester & A. Loll (Arizona State U.)

Discovery of H_2 & survey with Spartan

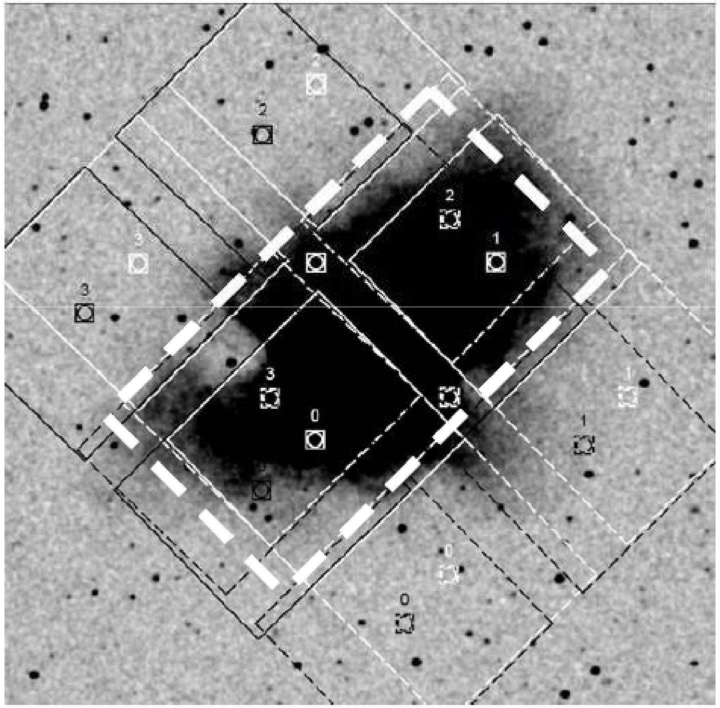
- Graham, Wright, & Longmore (1980) used a circular variable filter with a 20” aperture.
  - Detected H_2 in 2/3 filaments
  - H2 survives flux of photons & particles.
- Spartan survey
  - Cover entire nebula
  - Subarcsec resolution to resolve emission & determine brightness ($erg/s/cm^2/sr$)
  - Two filters & Continuum 3
    - 2121.8nm H_2 line
    - Brγ



Apertures of GWL

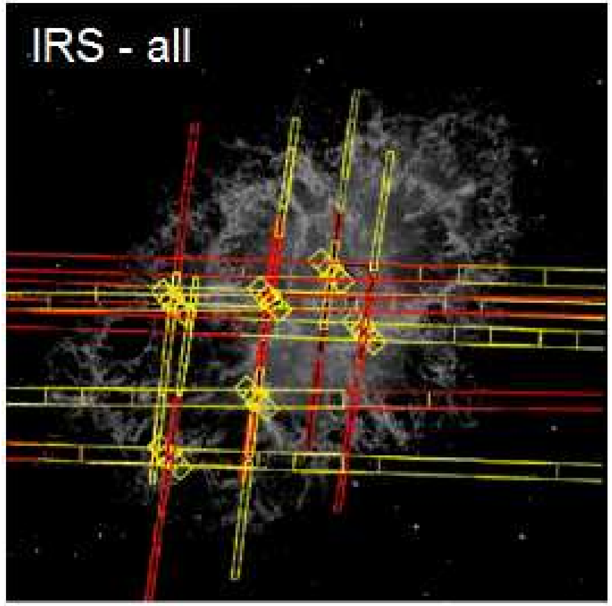
Spartan survey

- 24 Dec 2009–24 Mar 2010
- Detectors 0 & 1 on Crab and detectors 2 & 3 off. Then switch. Dither to cover gaps.
- 6.5, 7.0, & 9.3hr on H2, Brγ, & Cont 3.

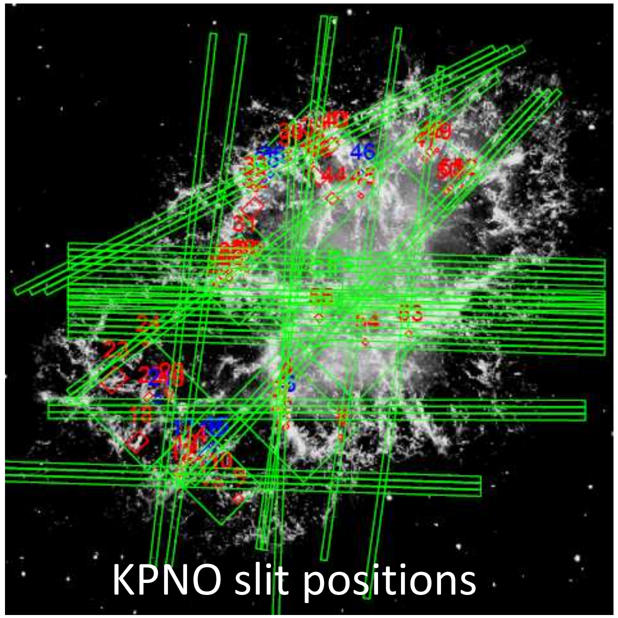


Follow-up observations

- OSIRIS K-band spectra of 7 knots
  - Nov 2010 – Jan 2011
  - 2-3hr on a knot.
- Existing Spitzer spectra
  - 0-0 S(0) to 0-0 S(7) lines of H_2.
  - Irregular coverage of H_2 knots
  - Full observations of Knot 1
- Kitt Peak Goldcam spectra

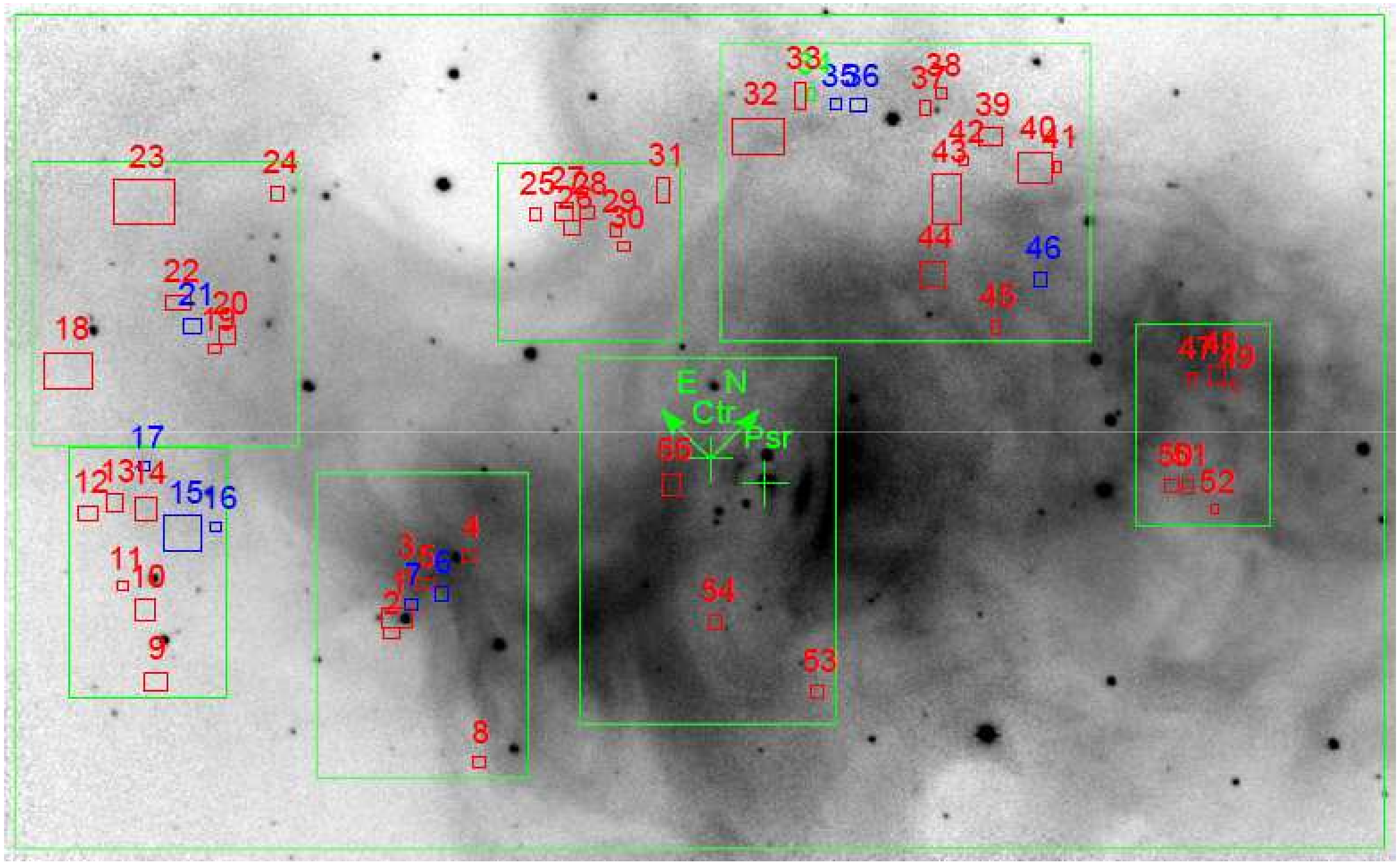


Existing Spitzer data. Box: High res.
Yellow & red slits: Low res.

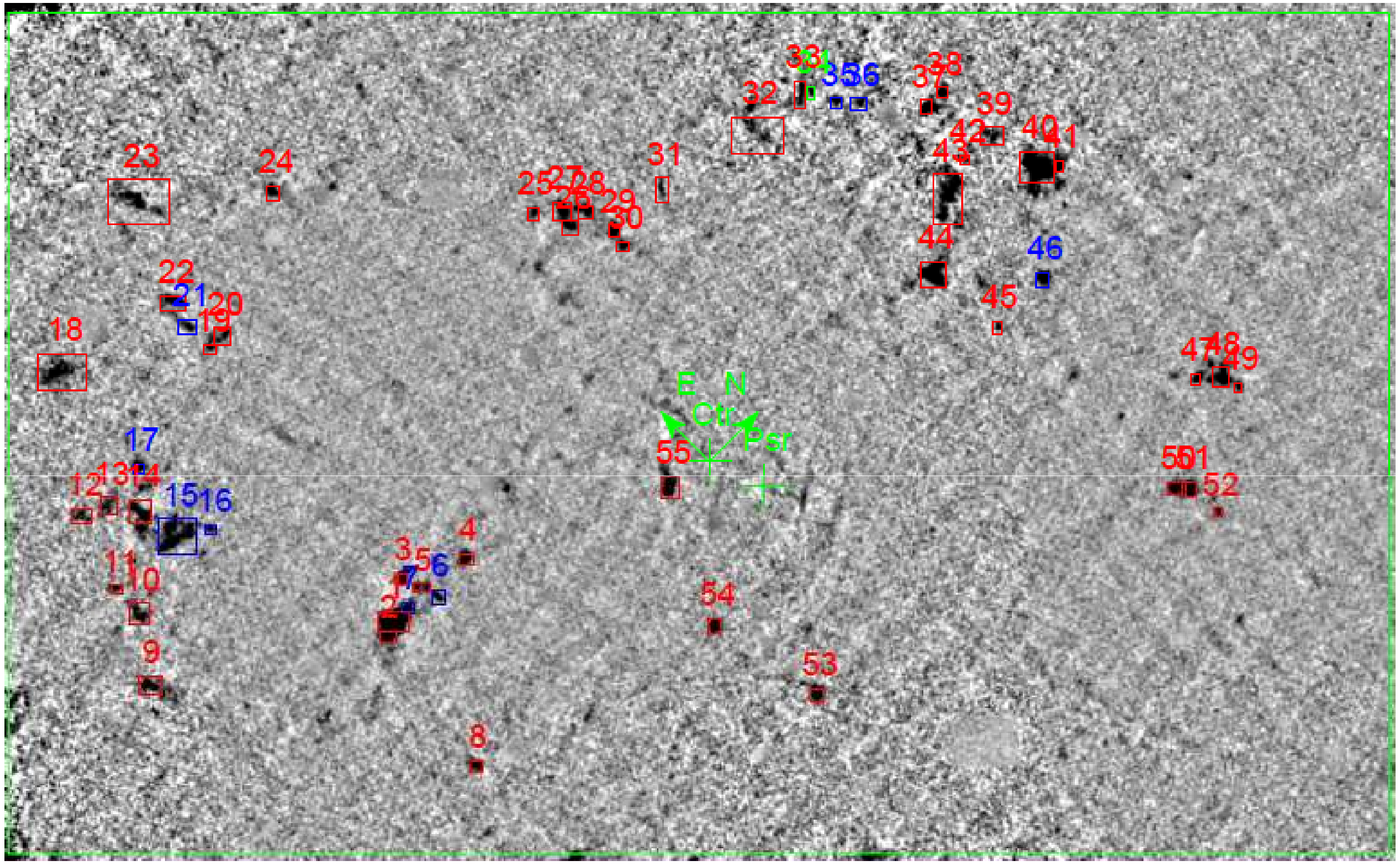


KPNO slit positions

Cont 3 (2208nm)

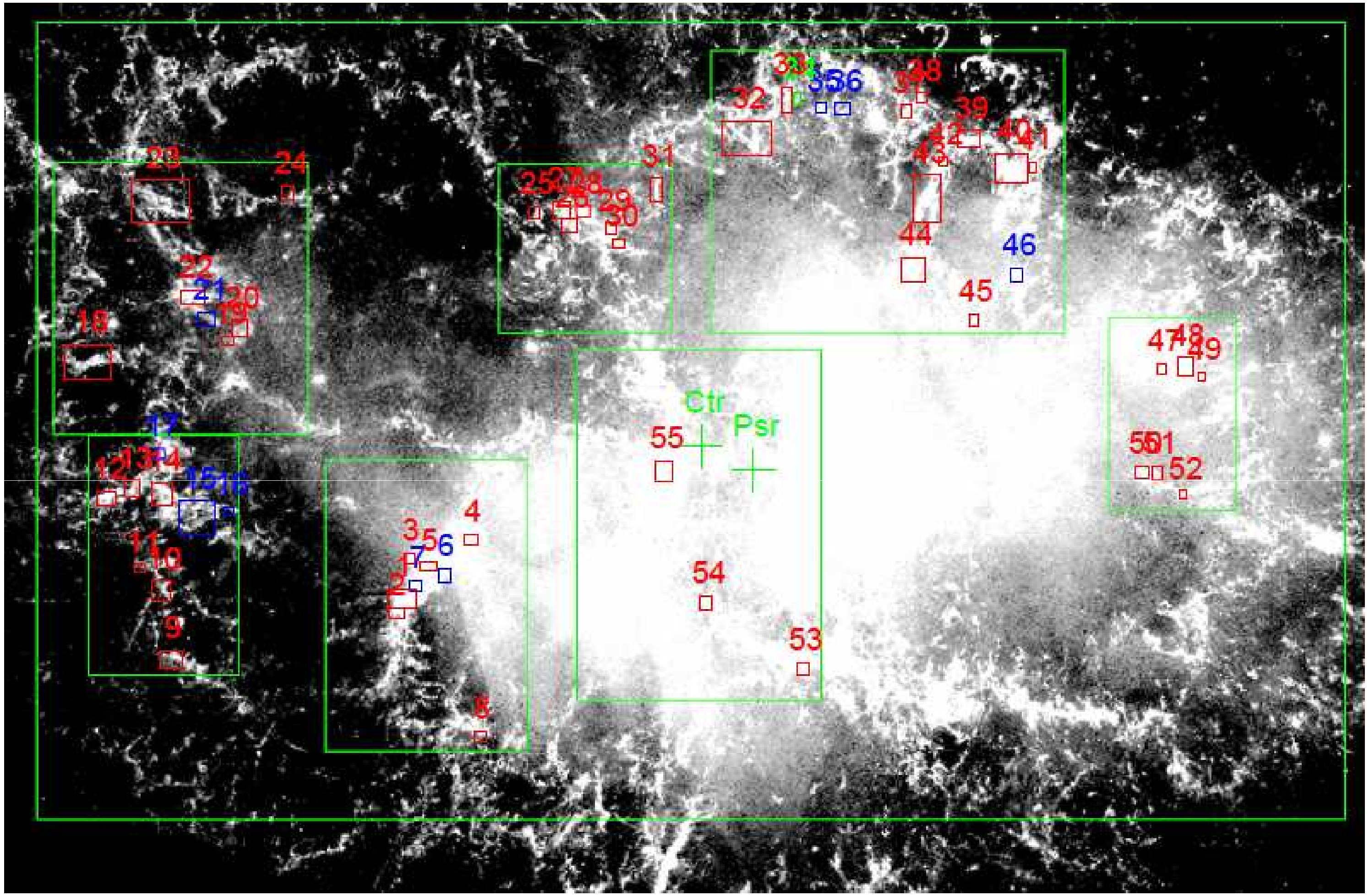


H2-Cont 3: 55 H_2 knots



- Median filtered with long vertical and horizontal kernels to eliminate detector features, mainly edges.
  - Residuals are diagonals.
- Stars were eliminated by hand.

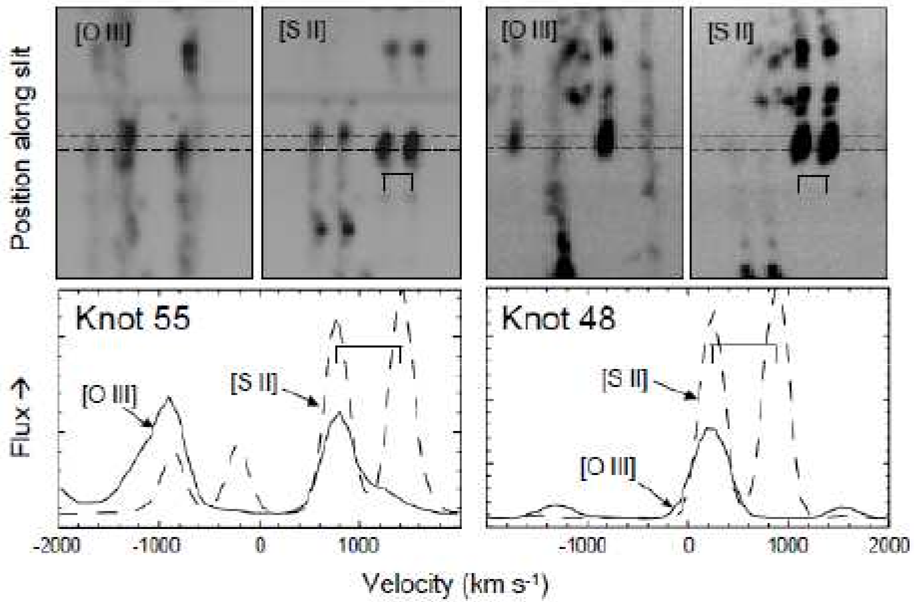
Knots & HST F631 [OI]



NASA, ESA, J. Hester & A. Loll (Arizona State U.)

Velocities

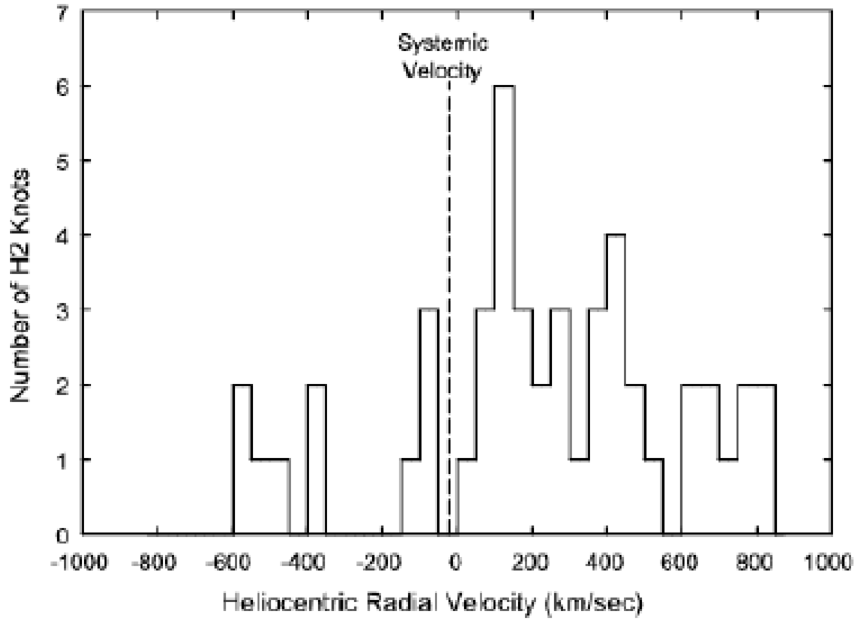
- KPNO Goldcam
  - 3700-7400Å at 6.3Å resolution
  - 3.8 arcsec $\times$5 arcmin slit
  - σ = 100km/s
- Knot 48 is simple.
  - [O III] and [S II] agree on one velocity.
- Knot 55 is has two velocities.
  - Choose one where [SII] is brighter.



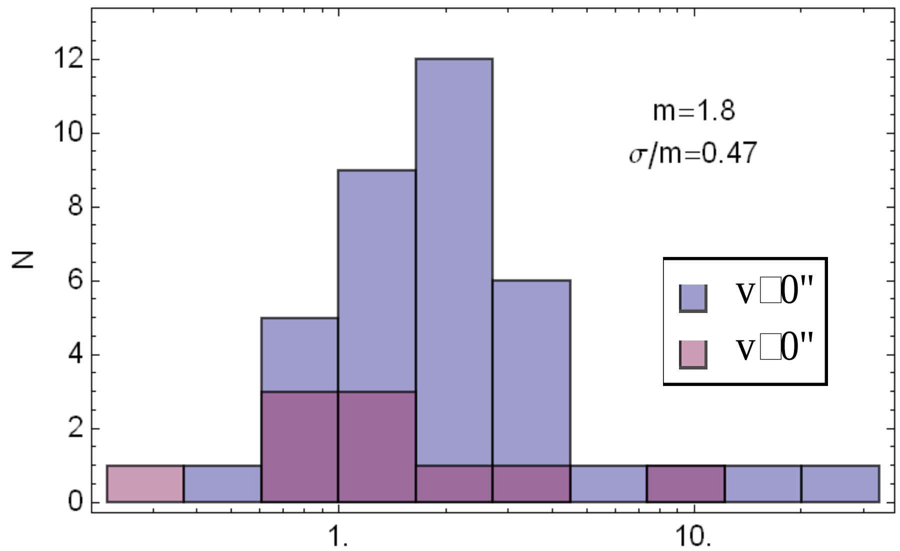
Spectra in the [O III] and [S II] regions, and the corresponding extracted [O III] (solid) and [S II] (dashed) profiles. The velocity scale is for [O III] 5007 and [S II] 6716

Velocity distribution

- Most knots are moving away. We primarily see the back side.
- Not due to H2 filter.
  - Cutoffs: -3000 & +1000km/s
- Two interpretations
  - The back is lit and the knot is opaque at 2μm
  - Large spatial variation.
    - Few knots in NW.



Histogram of Doppler velocity



Histogram of flux

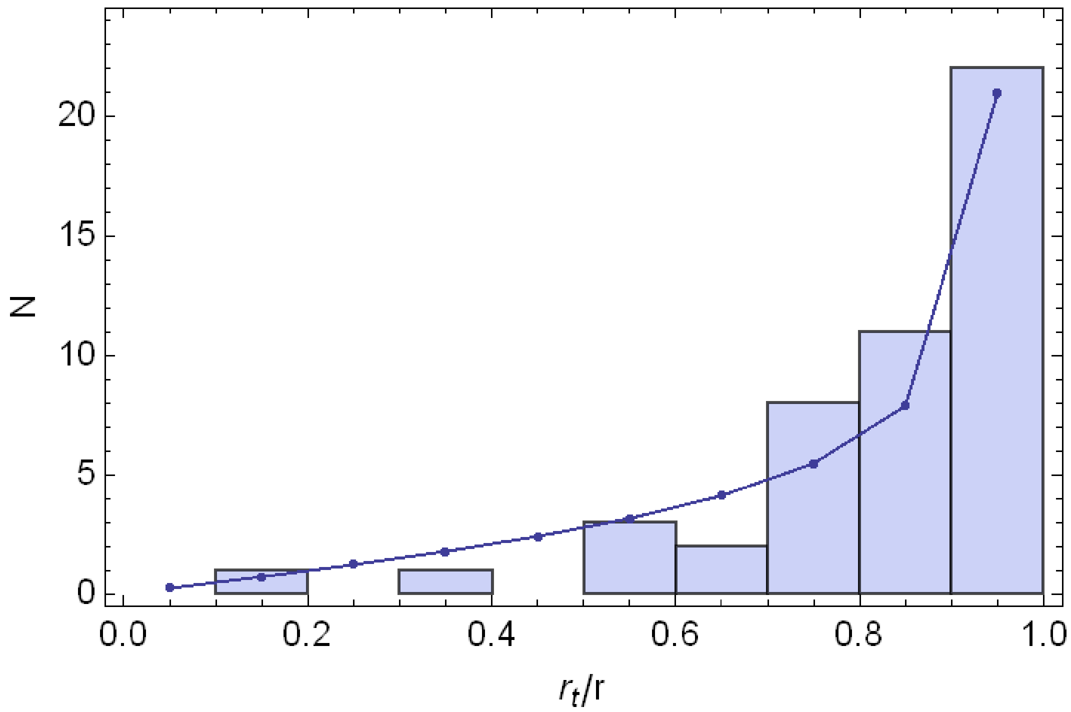
Spatial distribution of knots

- Find the 3-d distance r

$$\tan\theta = v_r t / r_p$$

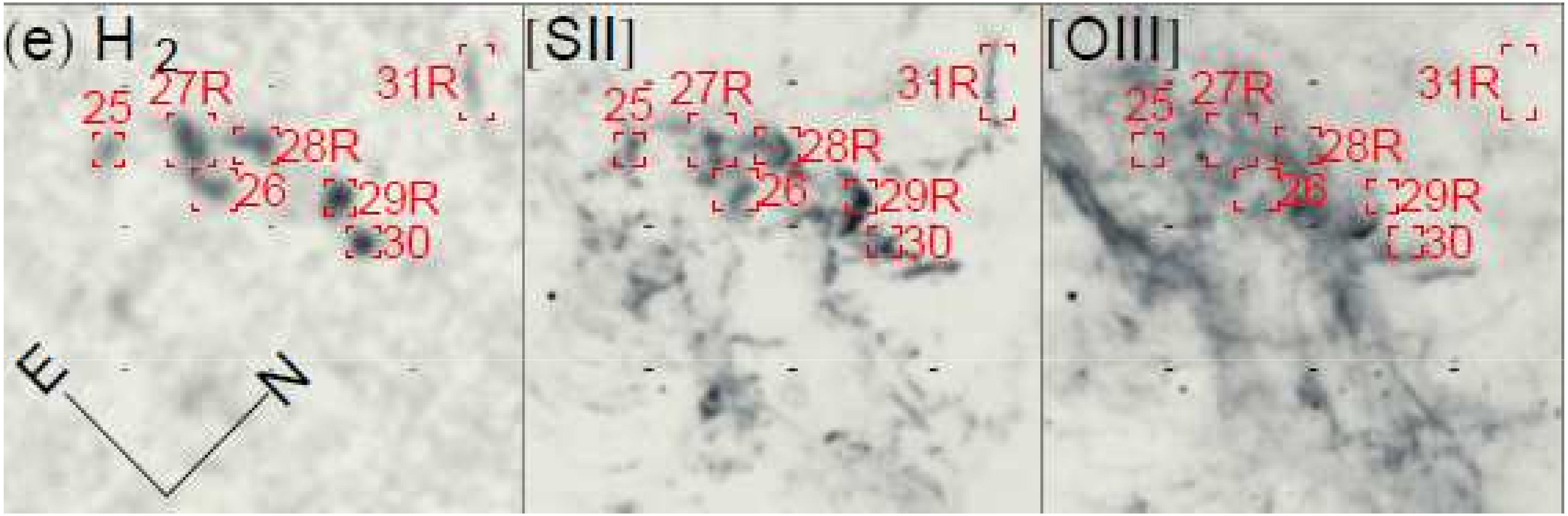
$$r = r_p / \cos\theta$$

- The knots are on a shell.
  - That means $v_r t \ll r_p$ for most of the knots.



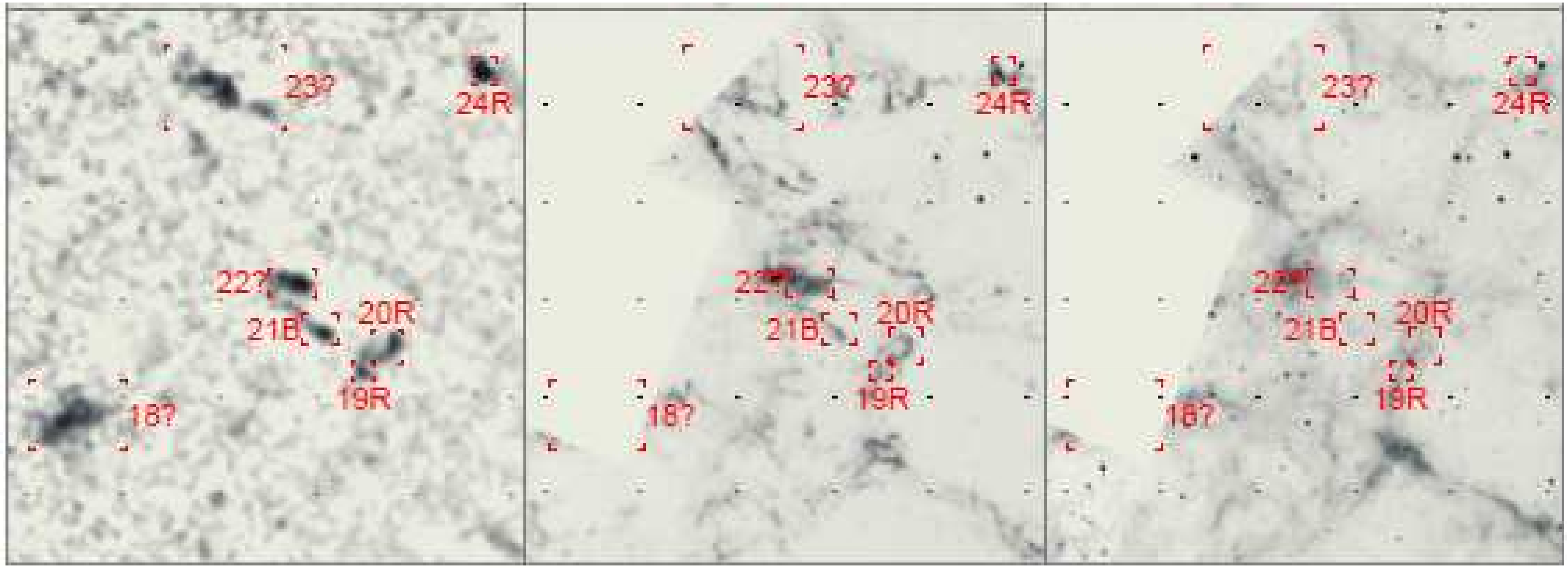
Histogram of r_{trans}/r.
The line assumes the objects are on a shell.

H_2 correlates with [SII], not [OIII]



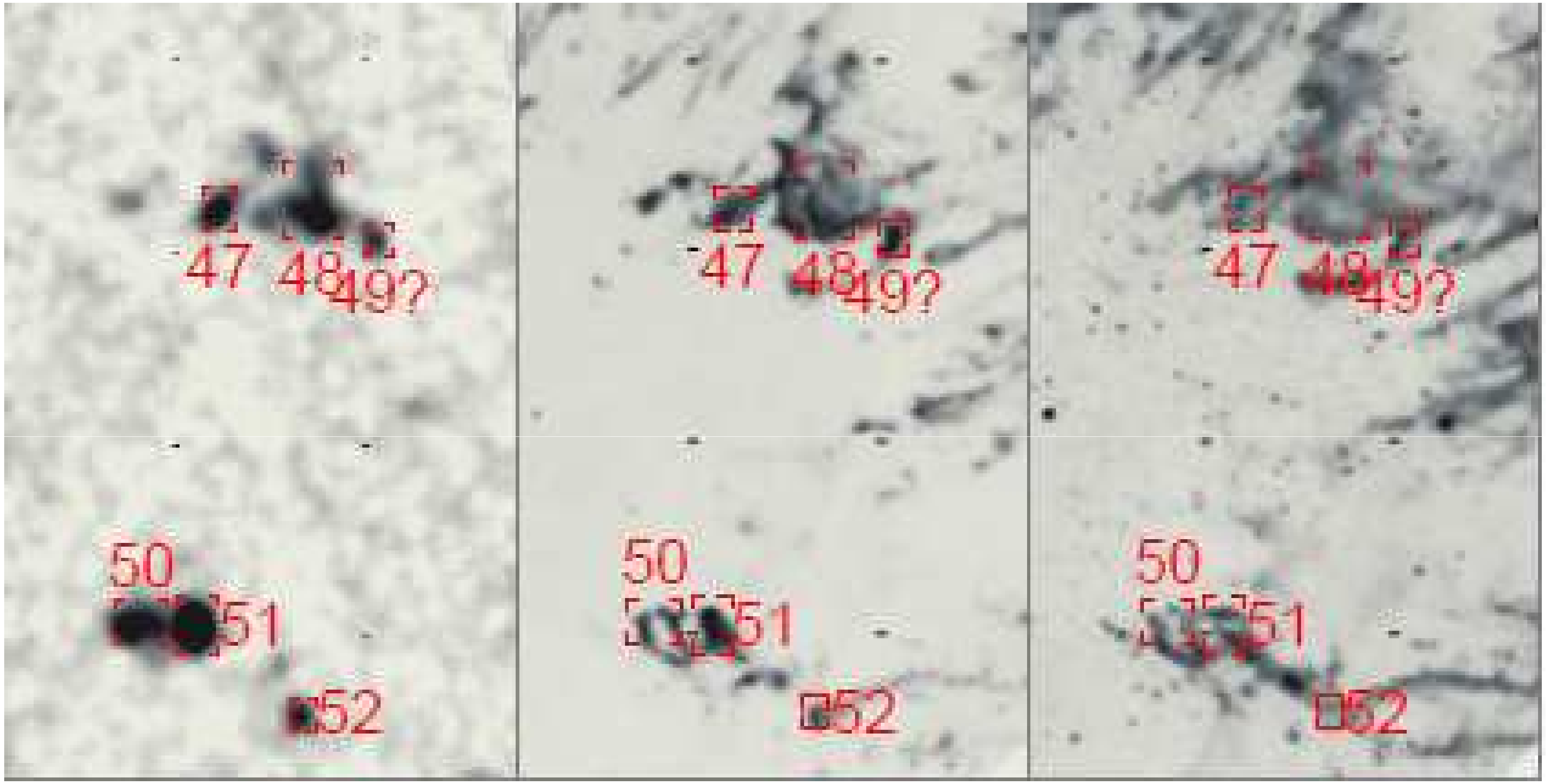
- Compare with [SII] (HST FN673) and [OIII] (HST FN502)

Knots in SE



23?
24R
22?
21B
20R
19R
18?
23?
24R
22?
21B
20R
19R
18?
23?
24R
22?
21B
20R
19R
18?

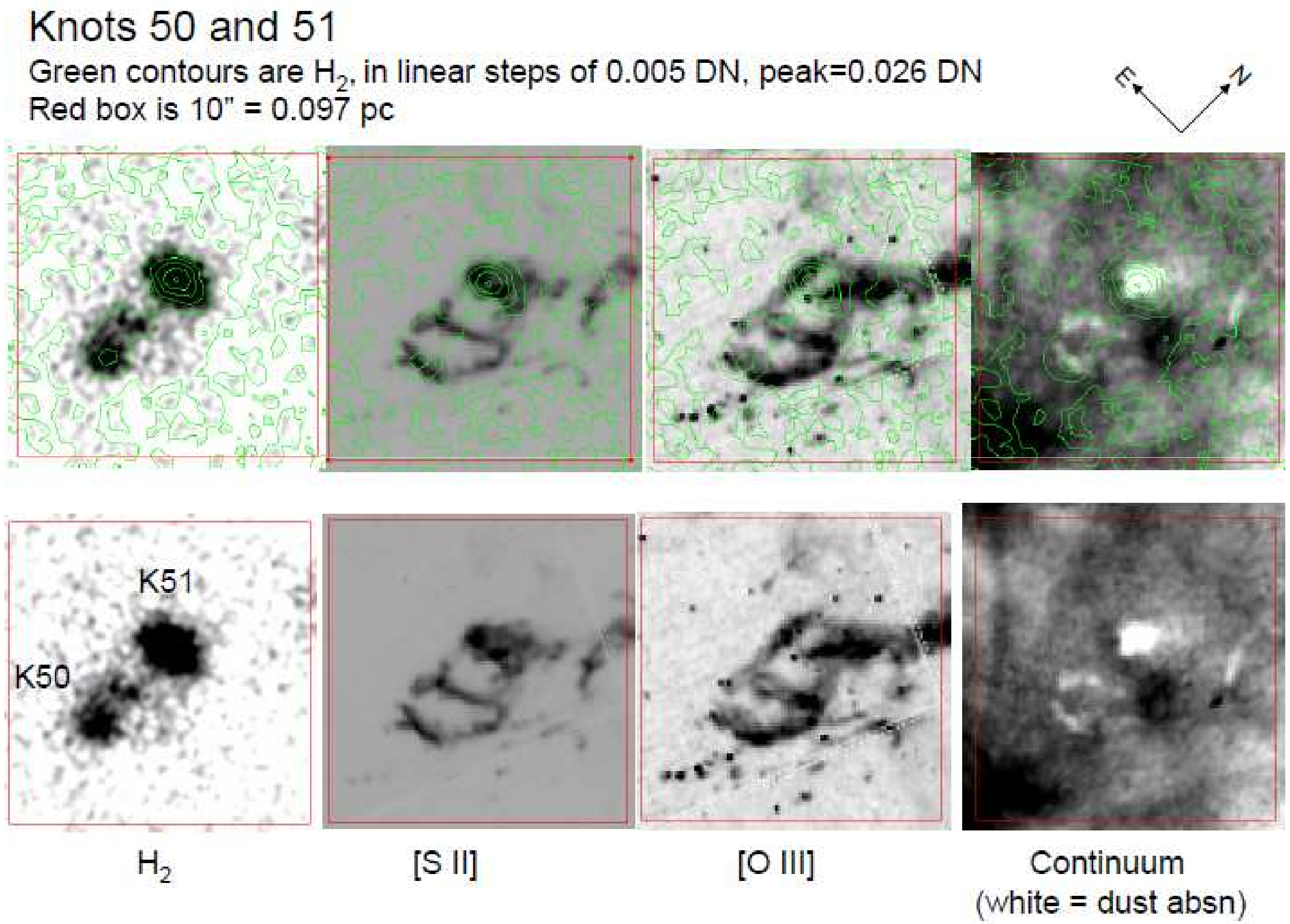
Knots in NW



- At ends of fingers

Knots 50 & 51, two in NW

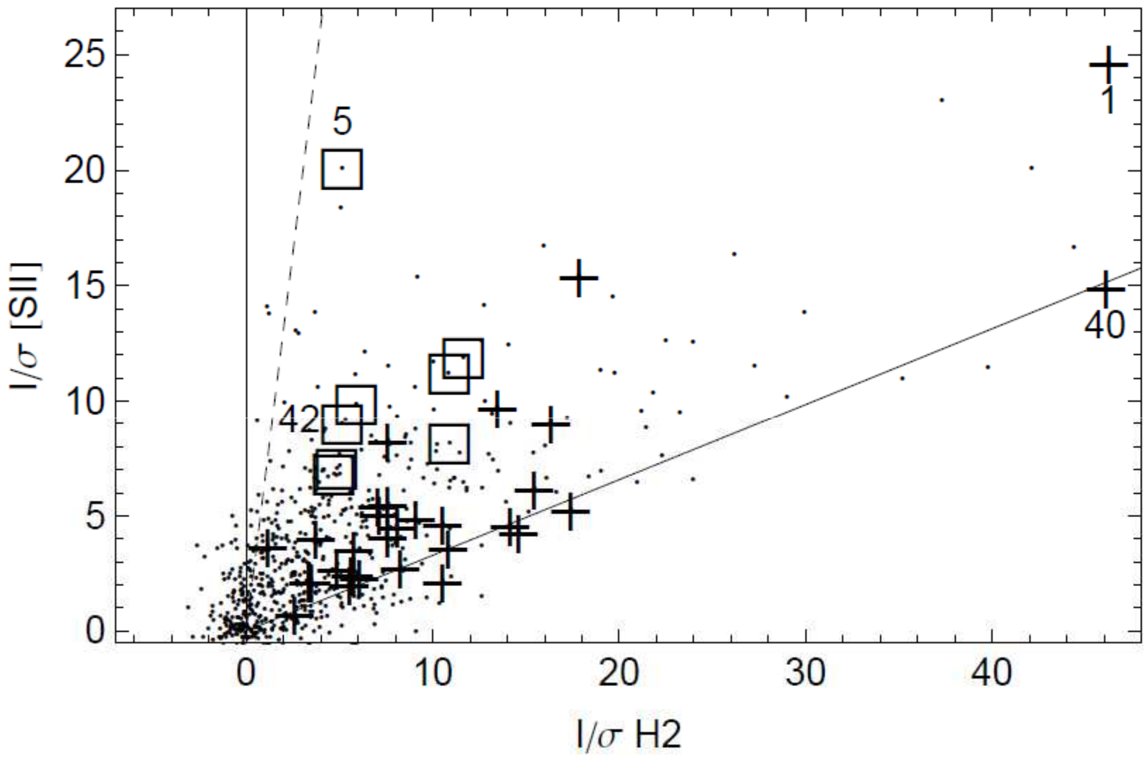
- At end of a finger (Rayleigh-Taylor?)
- Clean case.
  - At the edge
  - Isolated
- v_{51}=108km/s
- v_{50}=123km/s
  - Largest v_D=800km/s
- K51 is in a hole in [SII] & [OIII]
- Dust seen in absorption.



H2 vs. [SII] pixel by pixel

- Pixel-by-pixel correlation (in units of σ:

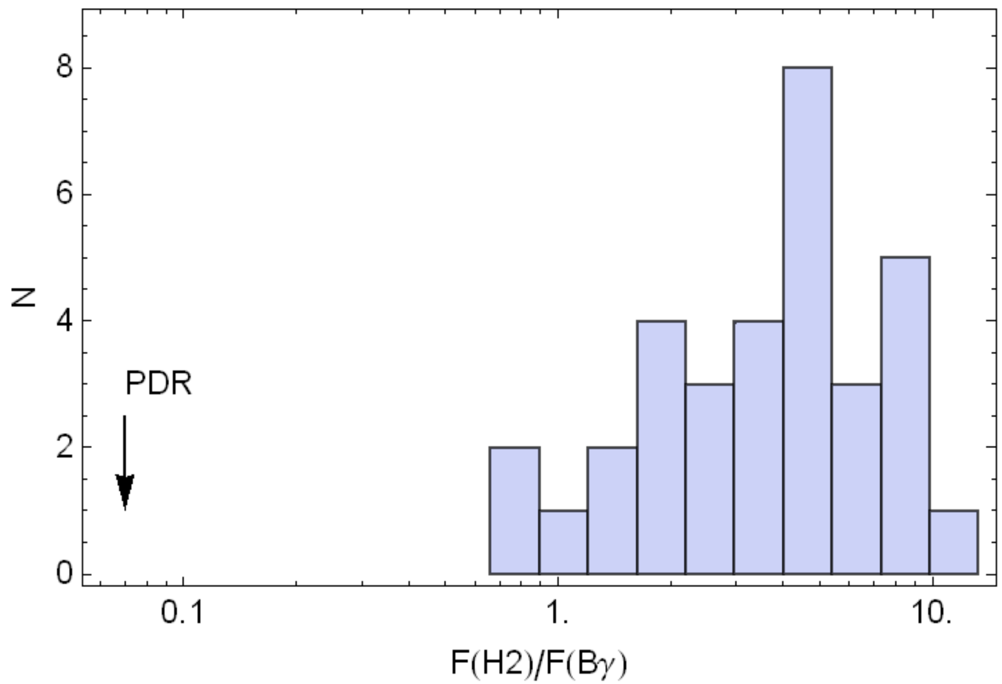
$$\frac{1}{3} I_{[SII]} < I_{H2} < 2I_{[SII]}$$



[SII] vs H2 pixel intensity in units of σ for pixels within H2 knots. Knot centers with Brγ/H2<0.25 (+) and Brγ/H2>0.6 (box).

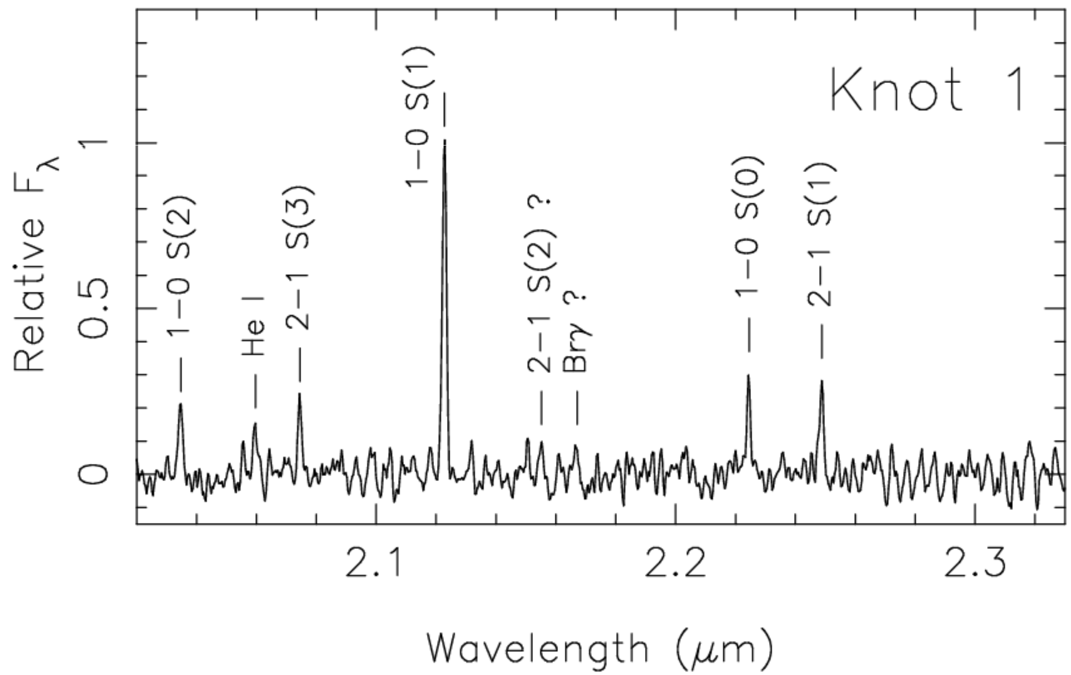
Brγ

- H_2/Brγ is high
  - Photo-dissociative region in Orion: 0.07
  - Filament in cooling flow in NGC1275: 8
- Spatial correlation between H_2 & Brγ is poor.
  - H_2 & [SII] are correlated.
  - H_2 & Brγ may be spatially separate.



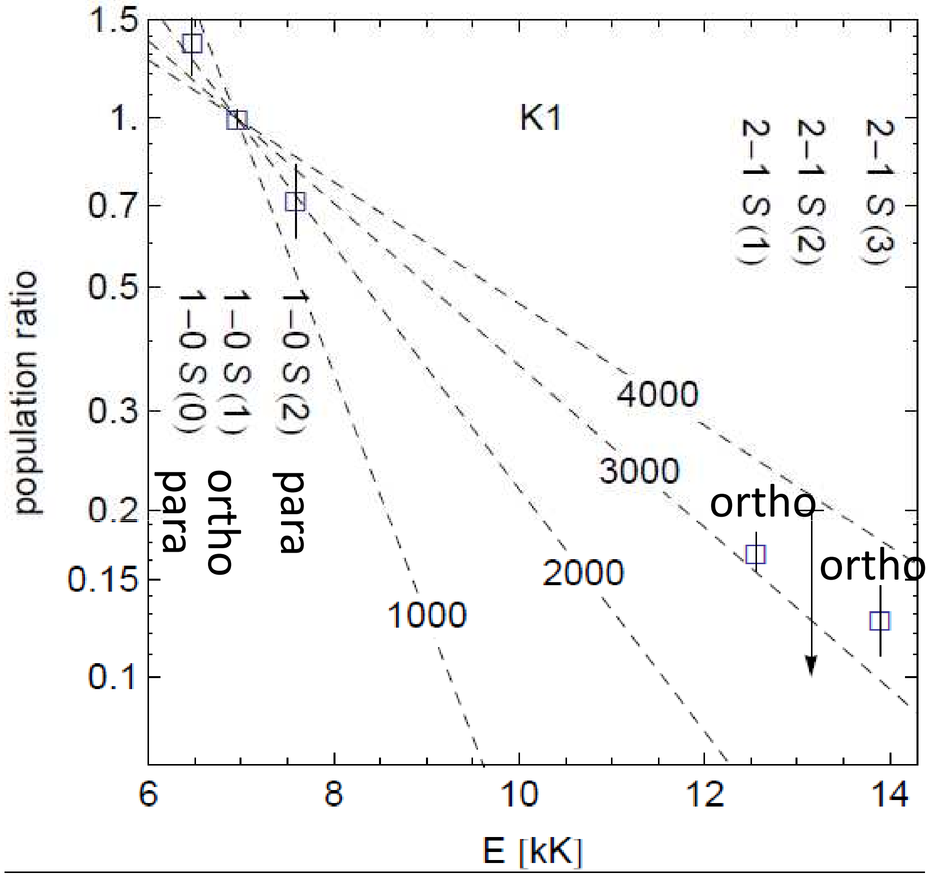
K-band spectra

- OSIRIS K-band spectra of 7 knots
  - Nov 2010 – Jan 2011
  - 2-3hr on a knot.



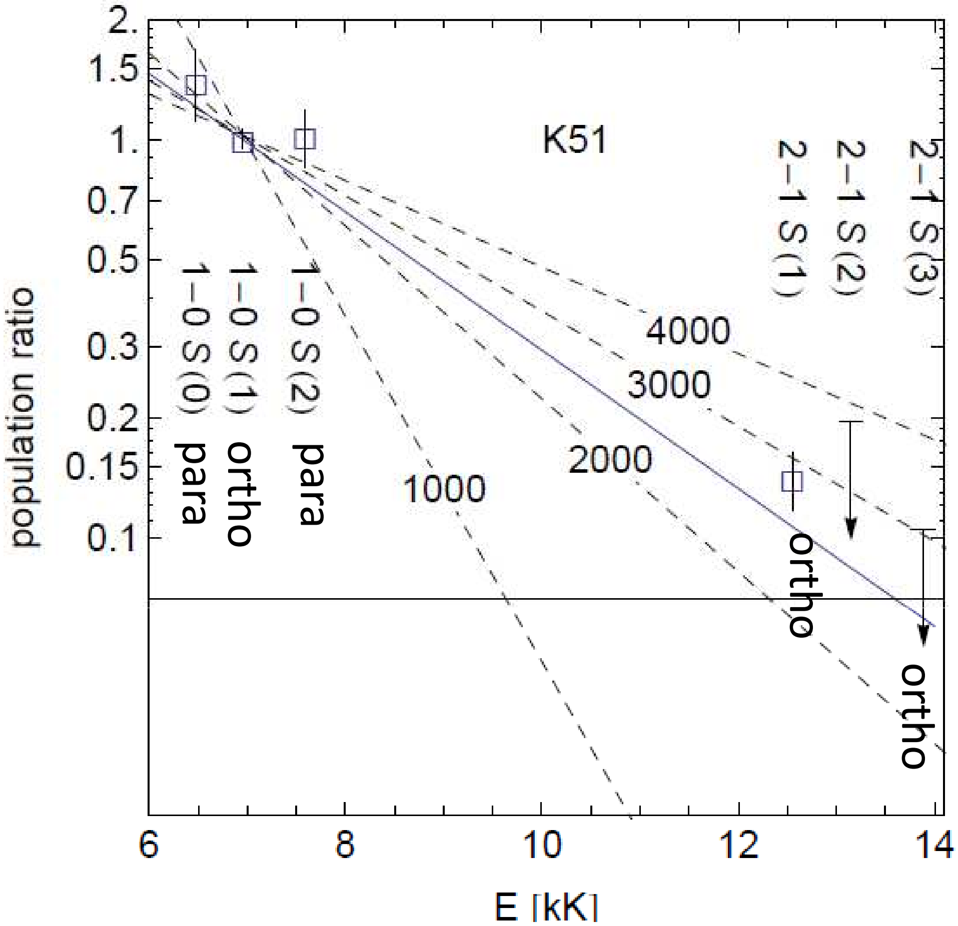
Boltzmann plot

- Boltzmann plot
  - Line intensity I/g_u vs excitation energy
  - In equilibrium,
    $$\frac{I}{g_u} = e^{-E/kT}$$
- Strongest line 1-0 S(1) means
  - $\nu_u=1 \rightarrow \nu_l=0$
  - $J_u=3 \rightarrow J_l=1$ (S means $\Delta J=-2$)
- Exclusion principle couples nuclear spin and molecular rotation.
  - J=0, 2, 4, … and nuclear singlet (para)
  - J=1, 3, 5,… and nuclear triplet (ortho)



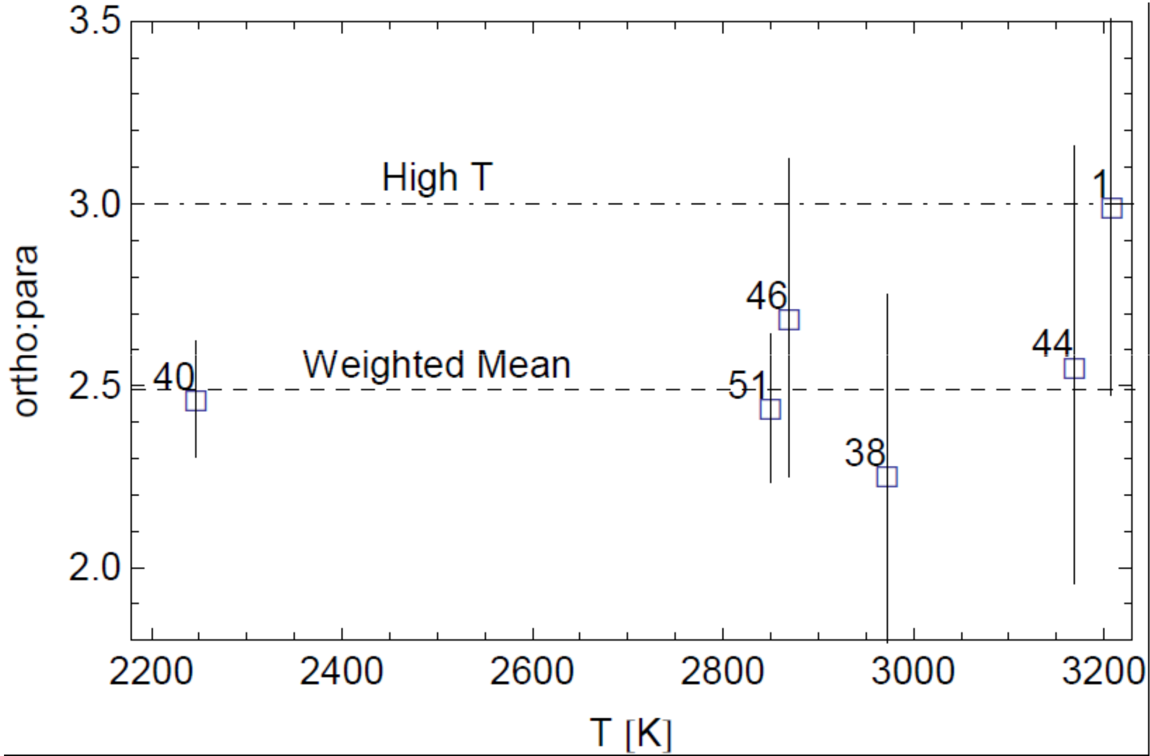
Ortho-para ratio

- Ratio of number of ortho to para hydrogen (OTP) depends on temperature
  - Ortho means J=1, 3…, which has higher energy than J=0.
  - At high T, OTP=3because ortho is a triplet.
  - At T=97K, OTP=1.5
- Ortho and para conversion occurs by substituting a proton.
- In Knot 51, the para lines are too strong. OTP<3.



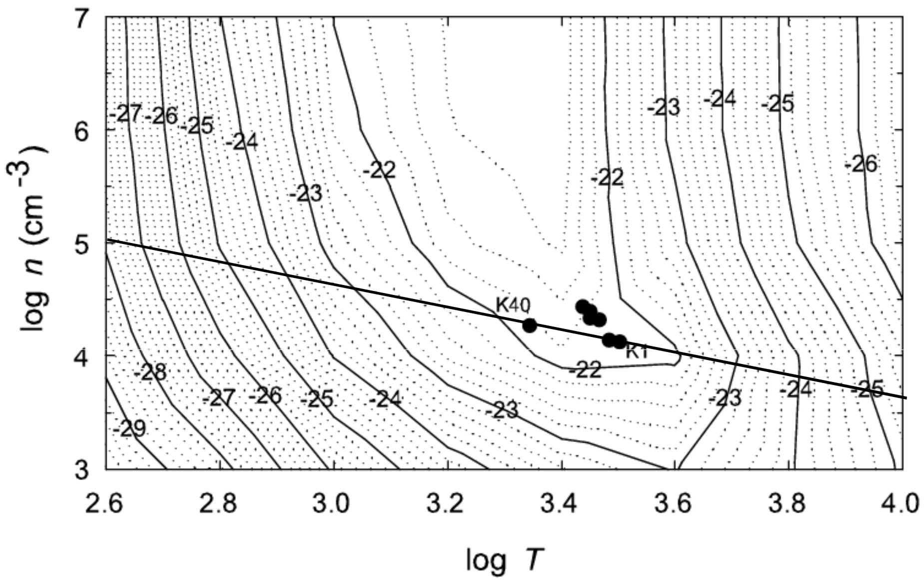
Ortho-to-para ratio of 6 knots

- Mean OTP=2.5 is a clue for H2 excitation.
- In equilibrium, OTP=2.5 for T=150K
- For ν=2 : ν=1, T=3000K



Temperature and density of knots

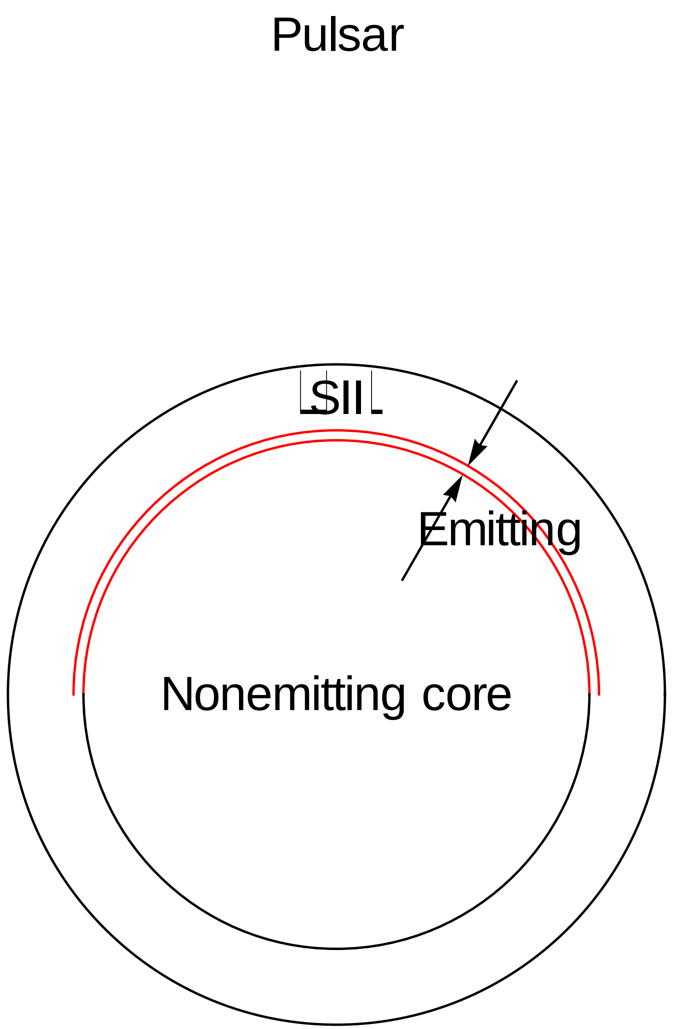
- We measured electron density from [SII] doublet. 2000cm^{-3}.
- Use measured excitation temperature of H_2 (3000K) as the gas temperature in molecular region.
- Assume pressure balance to get density in molecular region 1.4-2.1$\times 10^4$ cm^{-3}. (Assume T_{ion} = 15000.)
- Knots are at temperature & density of max emission.
  - Higher T $\Rightarrow$ dissociation
  - Higher n $\Rightarrow$ collisions de-excite



Measured H2 temperatures *Tmol* and deduced H densities *nmol* (points), plotted over contours of log10 of the surface brightness per H baryon 4π *j*(2.12μm)/*nmol* (erg cm3 s-1). Line is constant pressure.

Emission is from thin surface

- Emissivity of H2 (erg/s/cm3) & measured surface brightness of 1-0S(1) $\Rightarrow$ thickness of emitting region
$$l = 10^{14}\text{cm}$$
- Width of a knot (2arcsec at 2kpc) $w = 6{\times}10^{16}$cm. For all 6 knots,
$$\frac{l}{w} = 0.0011{\pm}0.0004$$



Mass of H_2 in the knots

Component	Mass
Progenitor	10
Filaments (ionized & neutral)	4.6 ± 1.8
Pulsar	1.4
Missing	4 ± 1.8

- Assume density of knot is that of the thin emitting region.
- Since temperature of non-emitting interior is cooler, density is higher.
- 55knots.

$$M_{\mathrm{H2}} \geq 1.0 M_{\mathrm{sun}}$$

- Fesen, Shull, Hurford 1997: $4\pm1.8M_{sun}$ is missing.

Questions

- How is $H2$ excited? Clues:
  - T=3000K
  - Ortho:para ratio <3, the high temperature equilibrium value.
  - Most knots are moving away.
  - Knots are on a shell.
- Other observations
  - GWL find [FeII] 1.646μ throughout a filament and also on our knots. Plan to observe.
  - SE knots look different morphologically. Are their temperatures different?
  - Is dust seen for all knots on the near side?
  - Reduce Spitzer data to see 0-0 transitions.