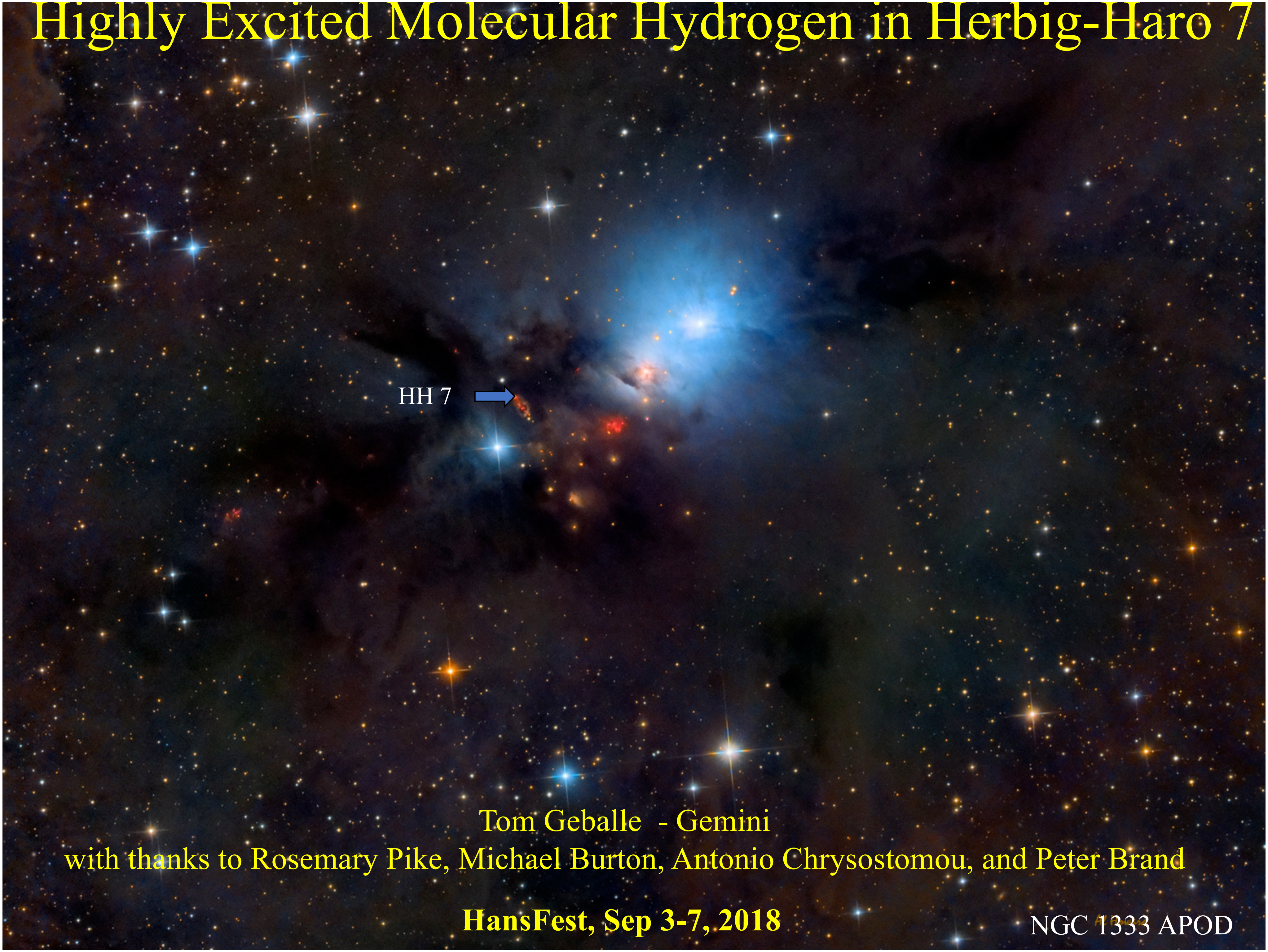
Highly Excited Molecular Hydrogen in Herbig-Haro 7



Tom Geballe - Gemini

with thanks to Rosemary Pike, Michael Burton, Antonio Chrysostomou, and Peter Brand

HansFest, Sep 3-7, 2018

The last time Hans and I collaborated (data from 1986!!)

HIGH SPECTRAL RESOLUTION OBSERVATIONS OF THE H_2 2.12 MICRON LINE IN HERBIG-HARO OBJECTS[1]

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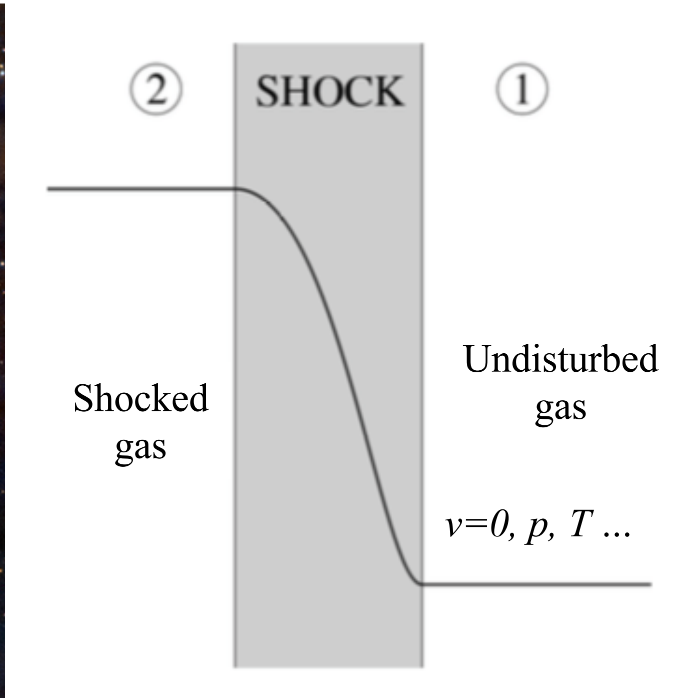
ABSTRACT

We have used the UKIRT infrared Fabry-Perot system to obtain high spectral resolution H_2 2.12 μm line profiles (resolution = 30–35 km s^{-1}) for a number of Herbig-Haro objects. Objects observed include HH 1/2, HH 7–11, HH 19, HH 32A, HH 40, and HH 43B; all are associated with jetlike features of collimated optical outflows. In most cases the velocity structure in the H_2 line resembles that of the higher excitation optical lines (e.g., Hα), but the FWHM and the maximum velocities of the H_2 lines are significantly smaller (by about a factor of 2). We conclude that for the observed objects the following two mechanisms seem to be most important for the H_2 emission: (1) shock heating of external molecular gas in the wings of the bow shock associated with the working surface of a high-velocity jet; and (2) shock heating of external molecular gas entrained in the flow by internal shocks occurring in the jet itself and/or in its boundary layer. The first mechanism is of course only relevant for Herbig-Haro objects associated with the jet's end (e.g., HH 1 or HH 32A), while the second one applies only to Herbig-Haro objects observed along the flow axis (e.g., HH 40 or HH 7–11).

Conclusion: Near the (high speed) tips of the jets, the observed H_2 must be in gas that is already entrained in the jet, otherwise it would be collisionally dissociated by the shock.



Following the 1976 discovery of bright H_2 By Gautier et al., line emission in OMC-1, in theoretical papers modelled the emission as the cooling of ambient molecular cloud material that had been suddenly heated by a jump-shock due to the impact of a protostellar wind.

All three models found that H_2 is fully dissociated by J-shocks with velocities > 20-24 km/s.

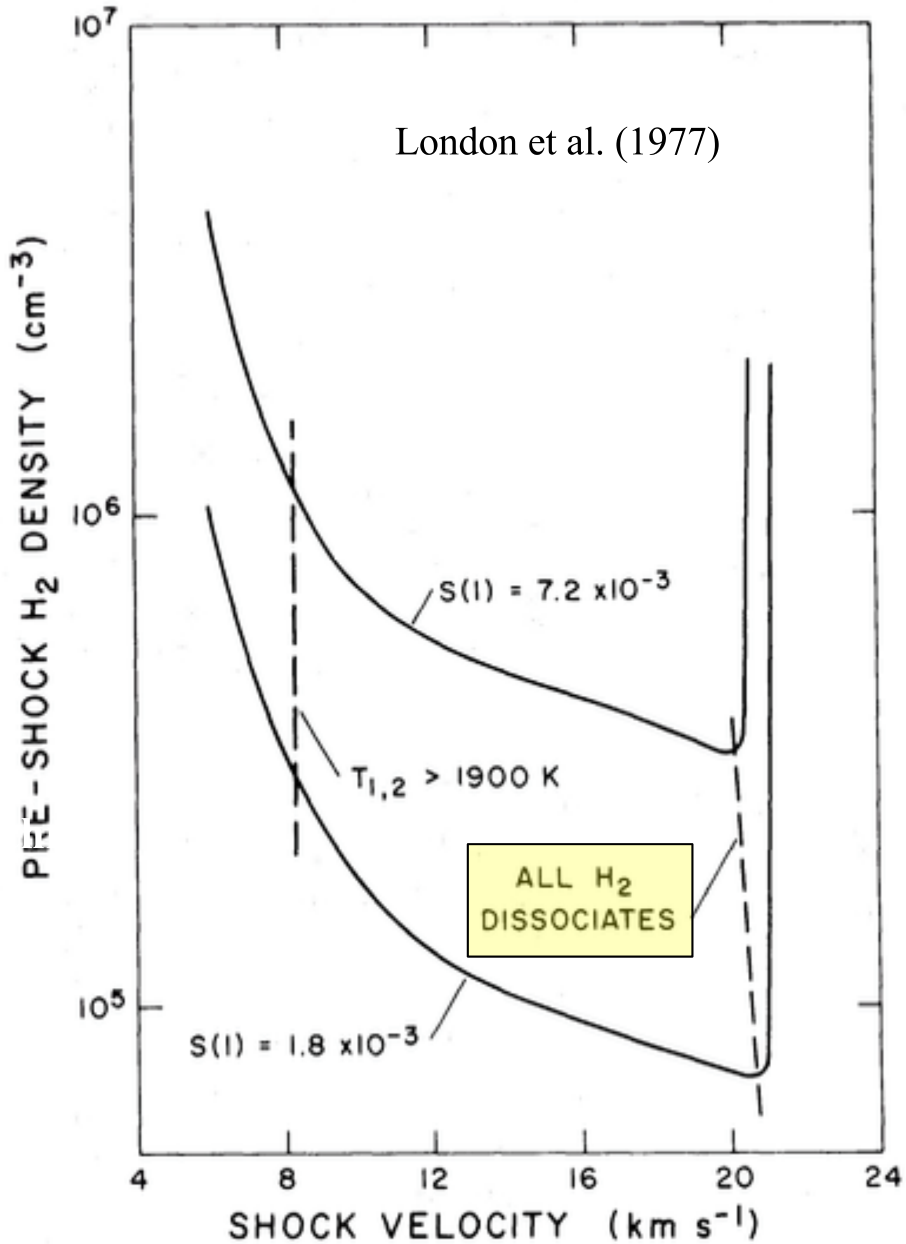


FIG. 2.—Range of parameters velocity v_0 and initial density n_0, to match H_2 infrared observations for case with $f = 1$. The low-velocity cutoff is for $T_{1,2} \gtrsim 1900$ K. The high-velocity cutoff is the velocity above which all the molecules are destroyed. The density limits at each velocity are set to match maximum and minimum contours on Grasdalen's map.

But the H_2 lines were soon found to be >>24 km/s wide.

VELOCITY PROFILES OF THE 2.1 MICRON H_2 EMISSION LINE IN THE ORION MOLECULAR CLOUD

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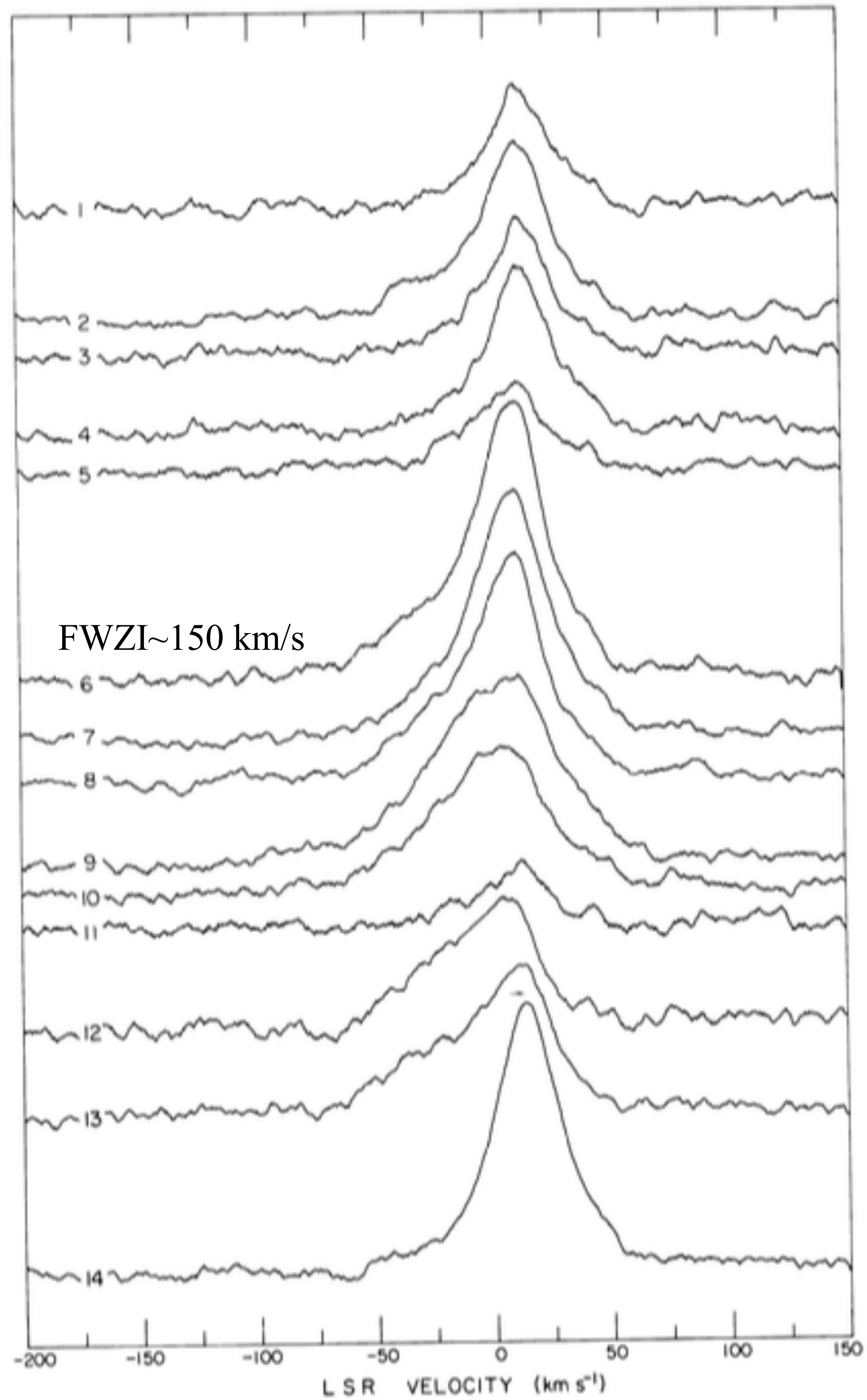
ABSTRACT

Spectra of the H_2 $v = 1\text{–}0$ $S(1)$ emission line in Orion, observed at various positions with a resolution of 20 km s^{-1}, are presented. The intrinsic full width at half-maximum of the line ranges from 18 to 58 km s^{-1} over the observed positions. Analysis of the line profiles shows that the emitting gas is probably expanding from a region near the BN and KL infrared sources at velocities typically of 40 km s^{-1} but as high as ~100 km s^{-1}, and that it is associated with the source of the broad lines seen in the spectra of many other molecules. Strong constraints are placed on models of the physical processes responsible for the broad emission lines.

Inconsistent with J-shocks

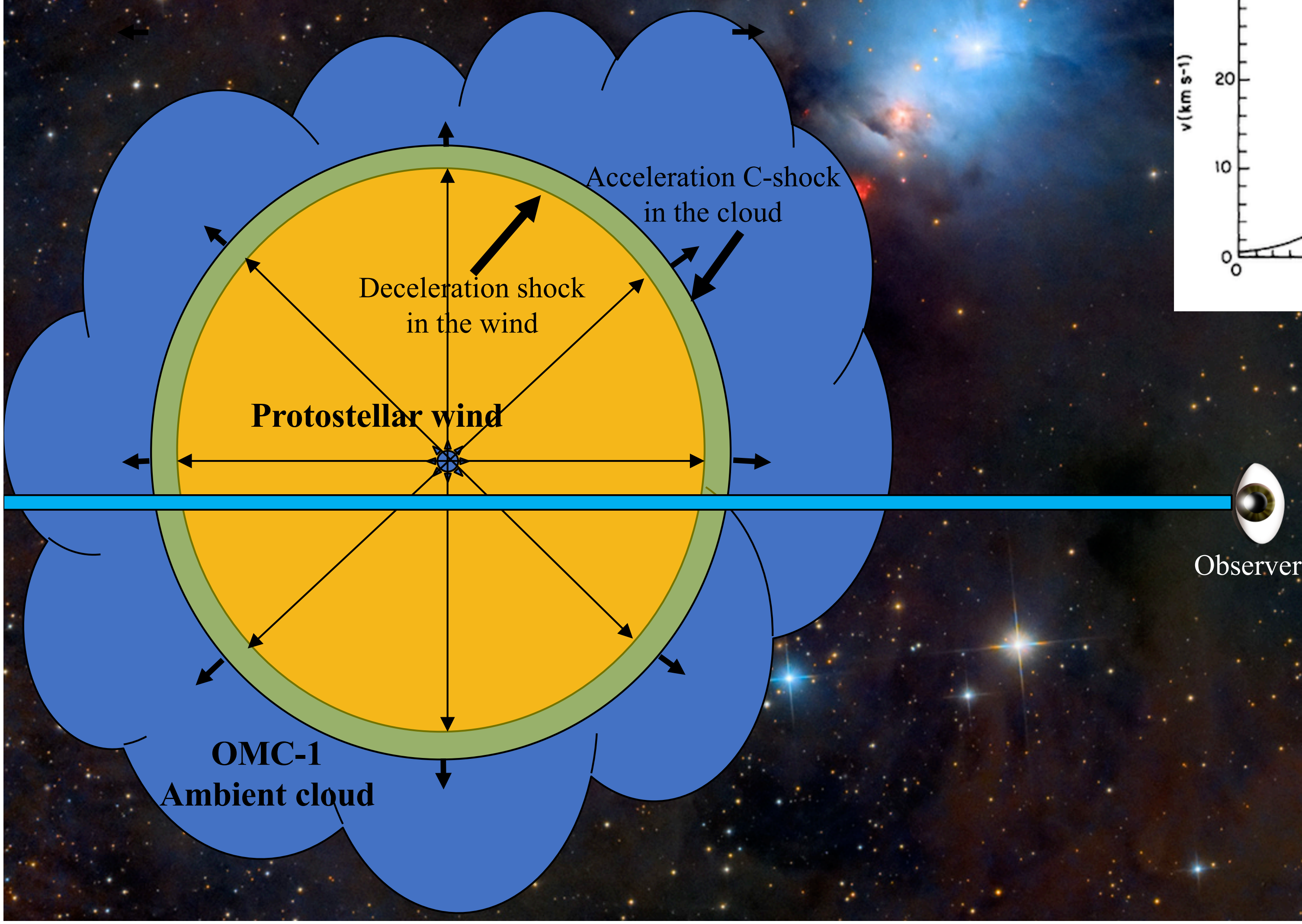


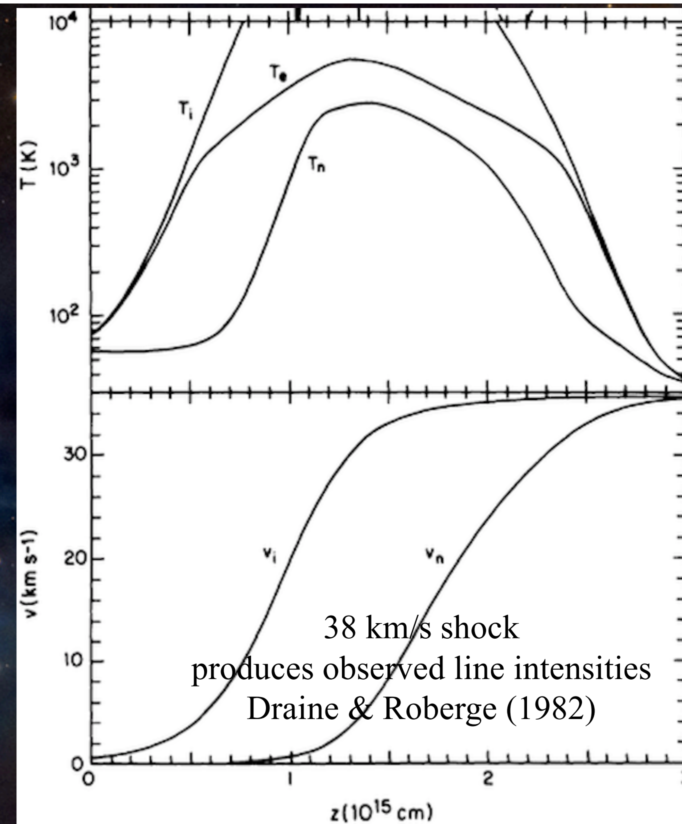
C-shocks (with magnetic precursors):

Realistic clouds have B-fields and are slightly ionized

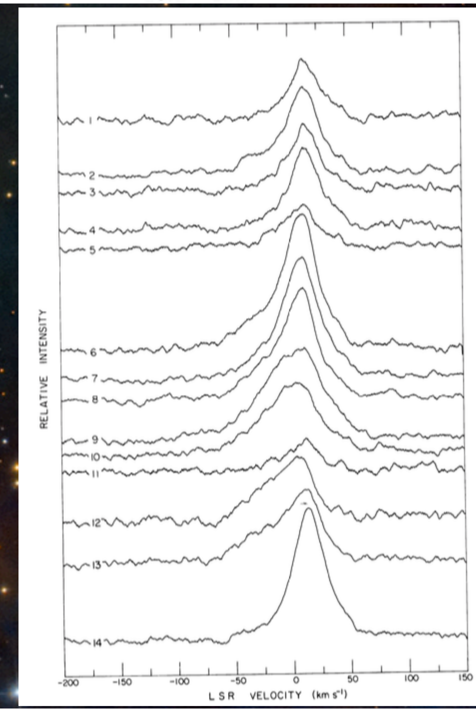
Ions stream ahead of neutrals, gradually accelerating the cloud before the neutral wind arrives.

Heating is much less extreme; little H_2 dissociated





38 km/s shock
produces observed line intensities
Draine & Roberge (1982)



RATIOS OF MOLECULAR HYDROGEN LINE INTENSITIES IN SHOCKED GAS: EVIDENCE FOR COOLING ZONES

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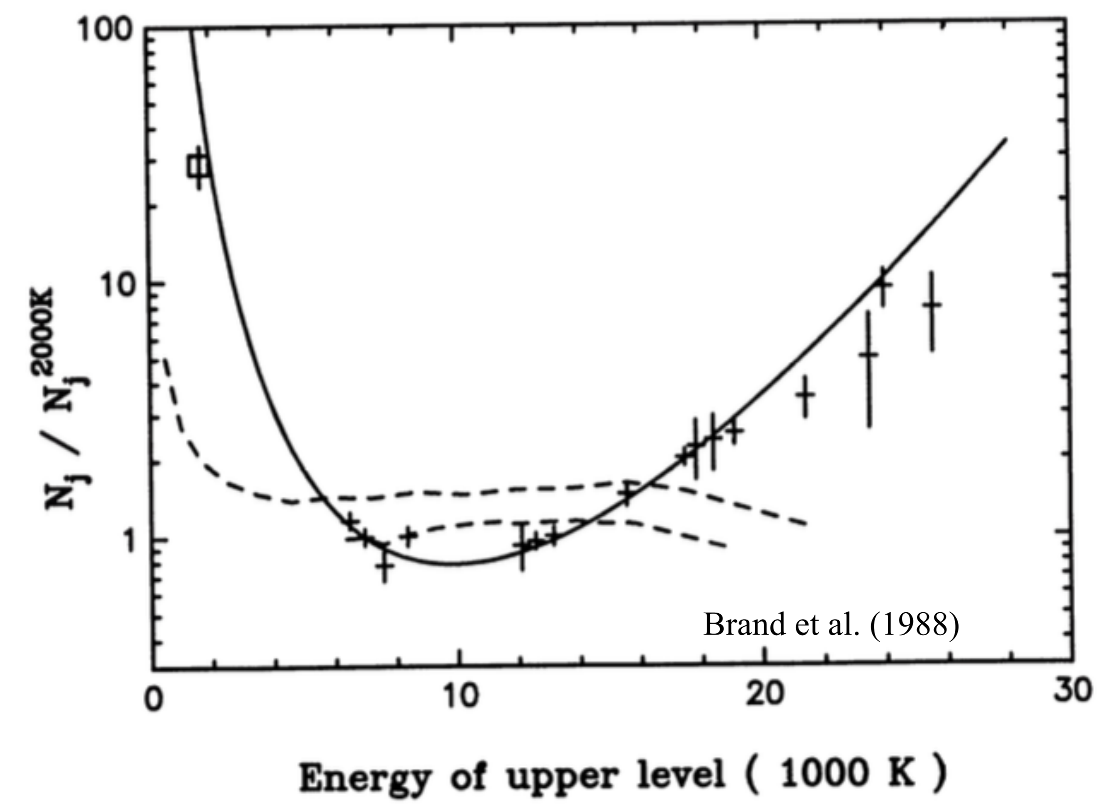
ABSTRACT

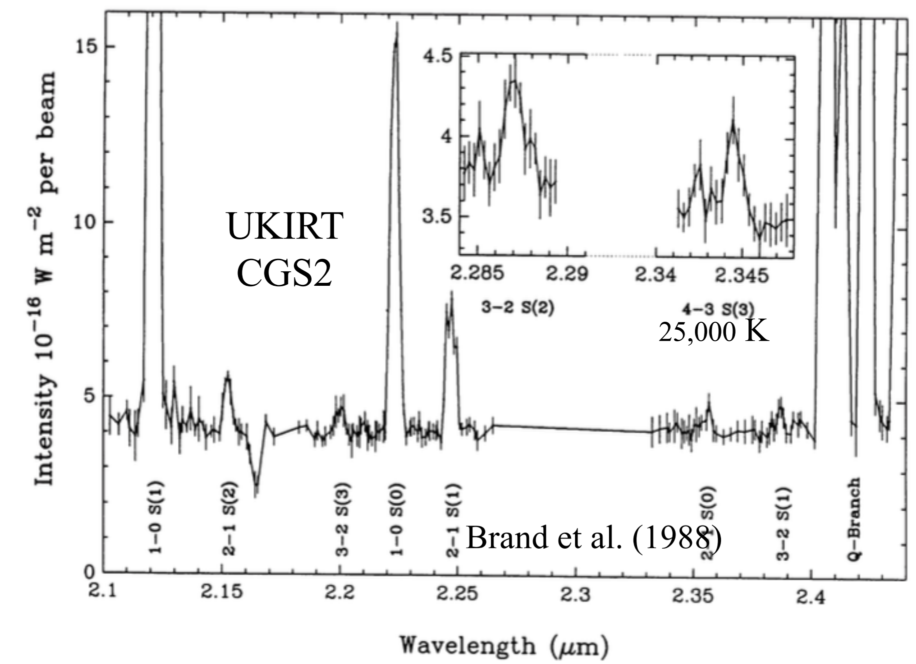
Column densities of molecular hydrogen have been calculated from 19 infrared vibration-rotation and pure rotational line intensities measured at peak 1 of the Orion molecular outflow. The run of column density with energy level is similar to a simple cooling zone model of the line-emitting region, but is not well fitted by predictions of C-shock models current in the literature.

BUT:

Lines from highly excited levels (20,000-25,000 K) are much stronger than predicted by C-shock models.

Relative line intensities closely match cooling curves for gas excited by J-shocks.





In a calculation with the detailed shape of the cooling function properly treated, a better fit will result. Current C-shock models provide a poor fit to the wide range of H_2 data now available, and it appears that a superposition of several C-shocks may be required. The dashed curves are from the C-shock calculations by Draine and Roberge (1982) and Chernoff, Hollenbach, and McKee (1982).

However, J-shocks at these velocities dissociate all H_2.

What is the cause of this conflict?

Is it due to superposition of C-shocks with different maximum temperatures in the 5" aperture?

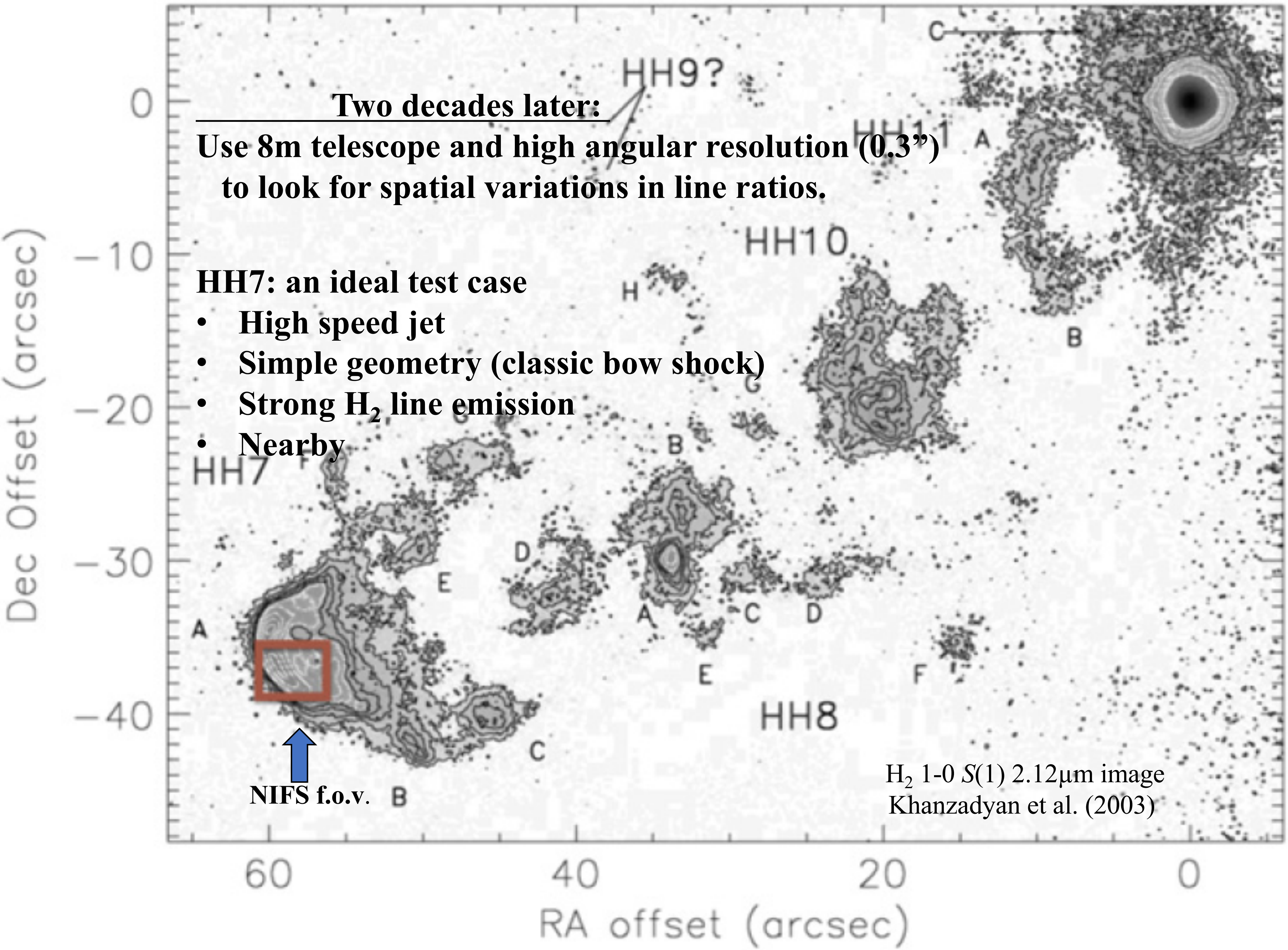
Al Howard

Two decades later:

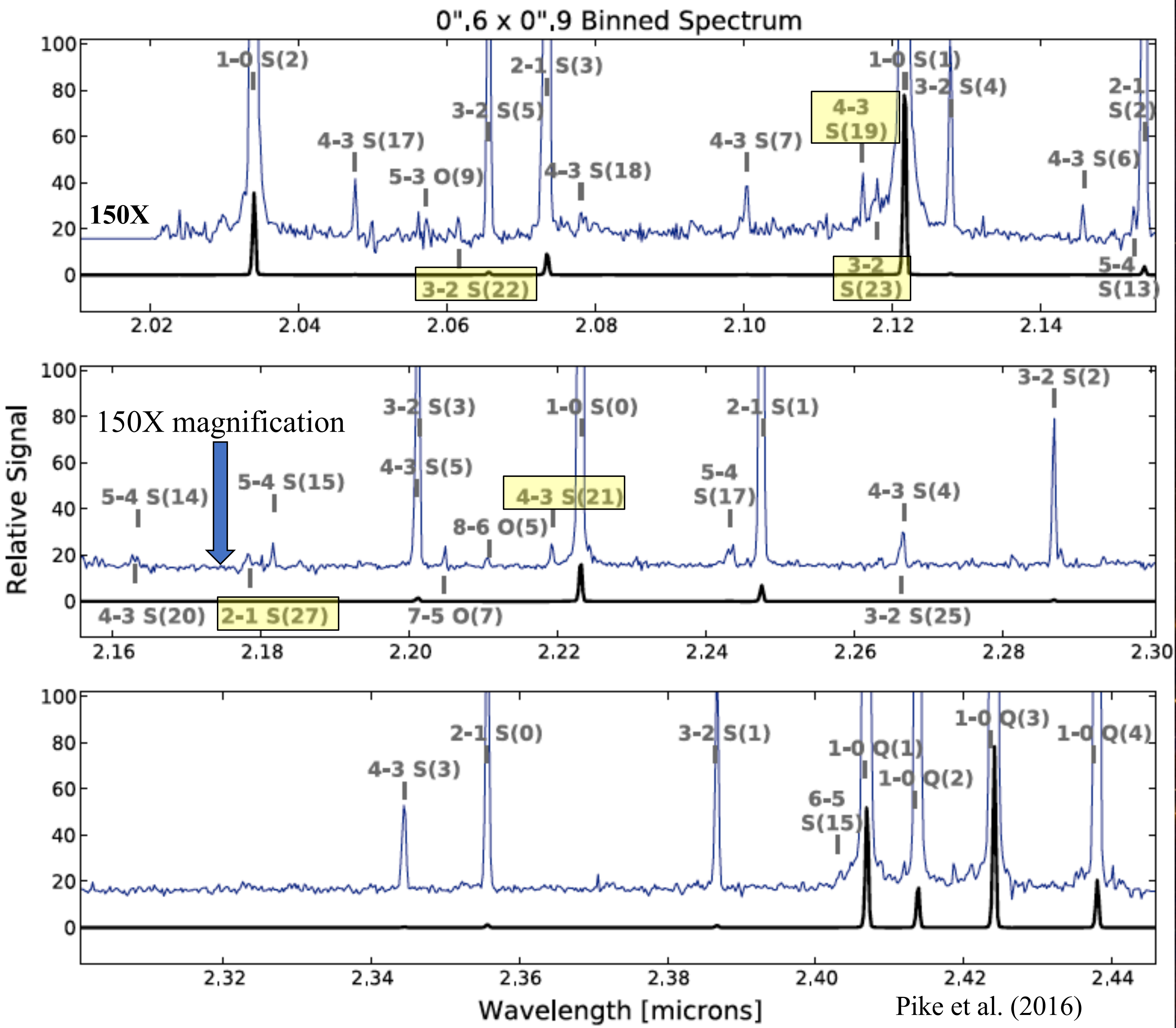
Use 8m telescope and high angular resolution (0.3”) to look for spatial variations in line ratios.

HH7: an ideal test case

- **High speed jet**
- **Simple geometry (classic bow shock)**
- **Strong H_2 line emission**
- **Nearby**



H_2 1-0 $S(1)$ 2.12μm image
Khanzadyan et al. (2003)



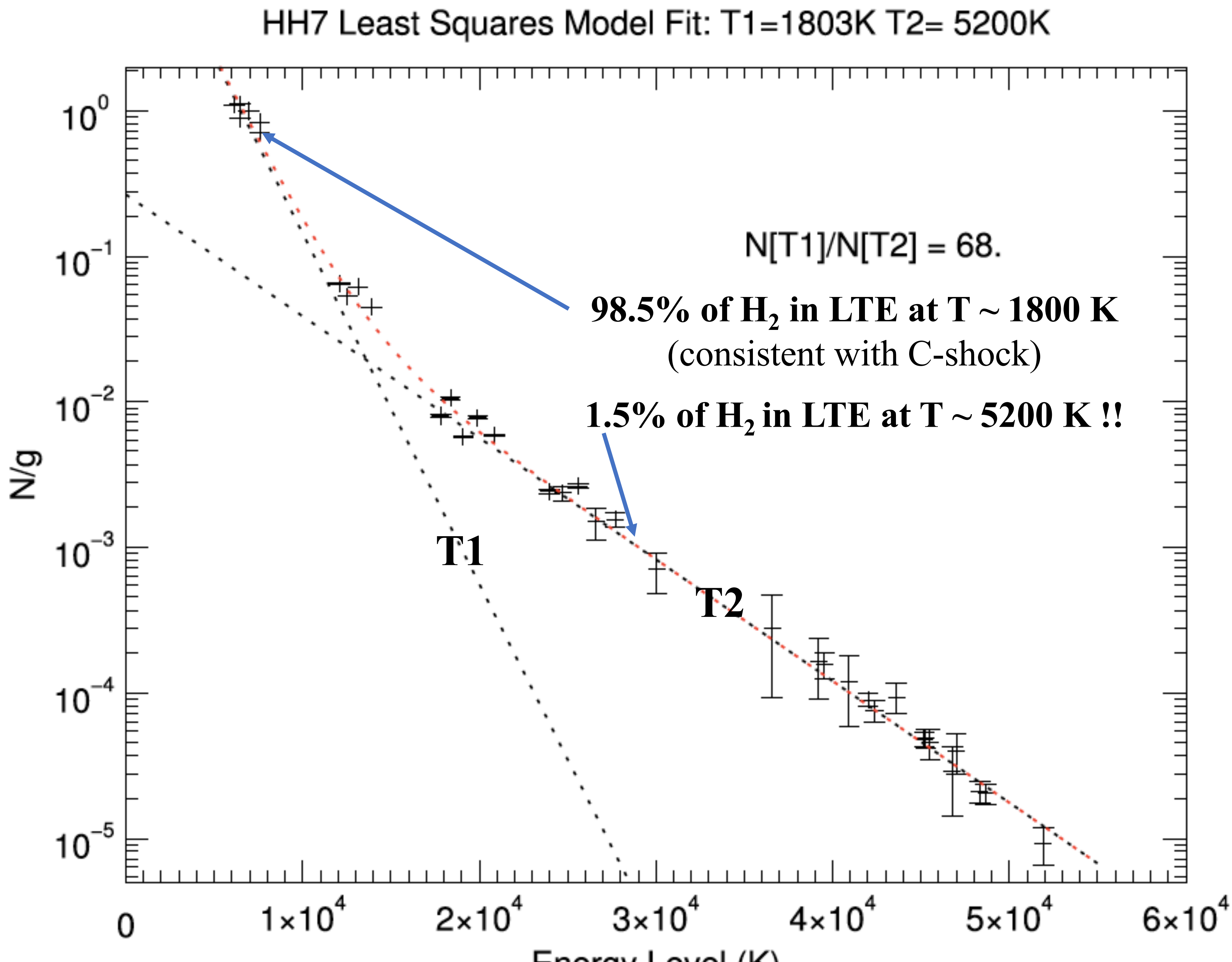
Pike et al. (2016)

HH7 LINE FLUXES (0.6” x 0.9” aperture)

Line ID	Rest λ Vac. (μm)[b]	Upper Level Energy (K)[b]	A 10^{-7} s^{-1}[c]	Observed Intensity[d]	Dereddened Rel. Intensity[e]
1–0 $S(2)$	2.0338	7585	3.98	80.8	43.0
4–3 $S(17)$	2.0475	42,022	13.4	0.39	0.20
5–3 $O(9)$	2.0571	30,064	1.56	0.13	0.07
3–2 $S(22)$	2.0616	47,012	...	0.13	0.07
3–2 $S(5)$	2.0656	20,857	4.50	3.2	1.7
2–1 $S(3)$	2.0735	13,890	5.77	23.4	12.0
4–3 $S(18)$	2.0781	43,614	16.7	0.17	0.09
4–3 $S(7)$	2.1004	27,707	2.98	0.34	0.17
4–3 $S(19)$	2.1163	45,204	19.9	0.35	0.17
3–2 $S(23)$	2.1181	48,690	22.2	0.25	0.12
1–0 $S(1)$	2.1218	6952	3.47	203.3	100.0
3–2 $S(4)$	2.1280	19,912	5.22	1.5	0.73
4–3 $S(6)$	2.1460	26,615	3.54	0.16	0.08
5–4 $S(13)$	2.1528	39,539	5.08	0.20	0.10
2–1 $S(2)$	2.1542	13,151	5.60	8.7	4.2
4–3 $S(20)$	2.1630	46,783	22.8	0.08	0.04
5–4 $S(14)$	2.1634	40,948	7.53	0.08	0.04
2–1 $S(27)$	2.1790	52,643	...	0.13	0.06
5–4 $S(15)$	2.1818	42,379	10.4	0.23	0.11
4–3 $S(5)$	2.2010	25,624	3.22	1.1	0.51
3–2 $S(3)$	2.2014	19,087	5.63	3.1	1.43
7–5 $O(7)$	2.2047	36,590	4.87	0.13	0.06
8-6 $O(5)$	2.2107	39,221	8.81	0.08	0.04
4–3 $S(21)$	2.2196	48,345	25.3	0.23	0.10
1–0 $S(0)$	2.2233	6472	2.53	40.5	18.4
5–4 $S(17)$	2.2433	45,275	16.1	0.27	0.12
2–1 $S(1)$	2.2477	12,551	4.98	16.2	7.2
3–2 $S(25)$	2.2663	51,939	30.7	0.14	0.06
4–3 $S(4)$	2.2668	24,734	4.02	0.36	0.16
3–2 $S(2)$	2.2870	18,387	5.63	1.6	0.69
4–3 $S(3)$	2.3445	23,955	4.58	1.1	0.46
2–1 $S(0)$	2.3556	12,095	3.68	3.6	1.49
3–2 $S(1)$	2.3864	17,819	5.14	2.6	1.06
6–5 $S(15)$	2.4030	45,526	12.1	0.17	0.07
1–0 $Q(1)$	2.4066	6149	4.29	127.5	51.1
1–0 $Q(2)$	2.4134	6472	3.03	40.5	16.2
1–0 $Q(3)$	2.4237	6952	2.78	176.3	70.0
1–0 $Q(4)$	2.4375	7585	2.65	51.5	20.3

NOTE: H_2 ground state dissociation energy ~ 51,000 K

Al Howard



Pike et al. (2016)

What is the origin of the 5200 K H_2 ?

1. UV fluorescence (common in clouds irradiated by hot stars),
   but non-thermal population distribution with T_{vib} >> $_{Trot}$ not observed.

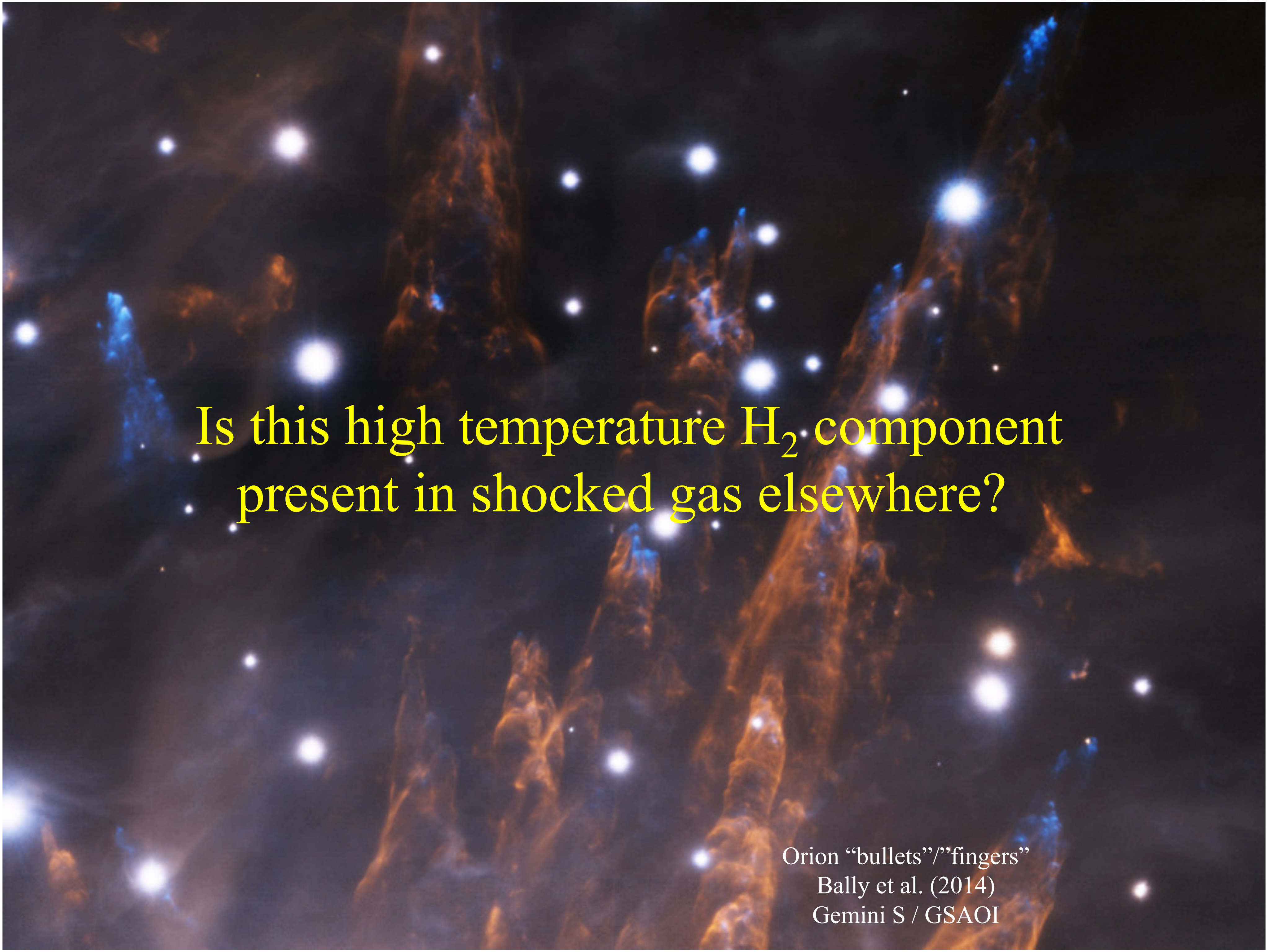
2. H_2 heated by ionization created by high speed (>50 km/s) shock,
   but no hydrogen recombination lines (e.g., Br γ) detected in HH7

3. Emission from newly formed H_2 ("formation pumping"):
   - Newly formed H_2 ejected from grain in highly excited states
   - E= 4.5 eV – grain surface potential ~ a few eV,
     (unknown distribution between *v* and *J* states)
   - 5000 K = 0.45eV, so no energy problem.

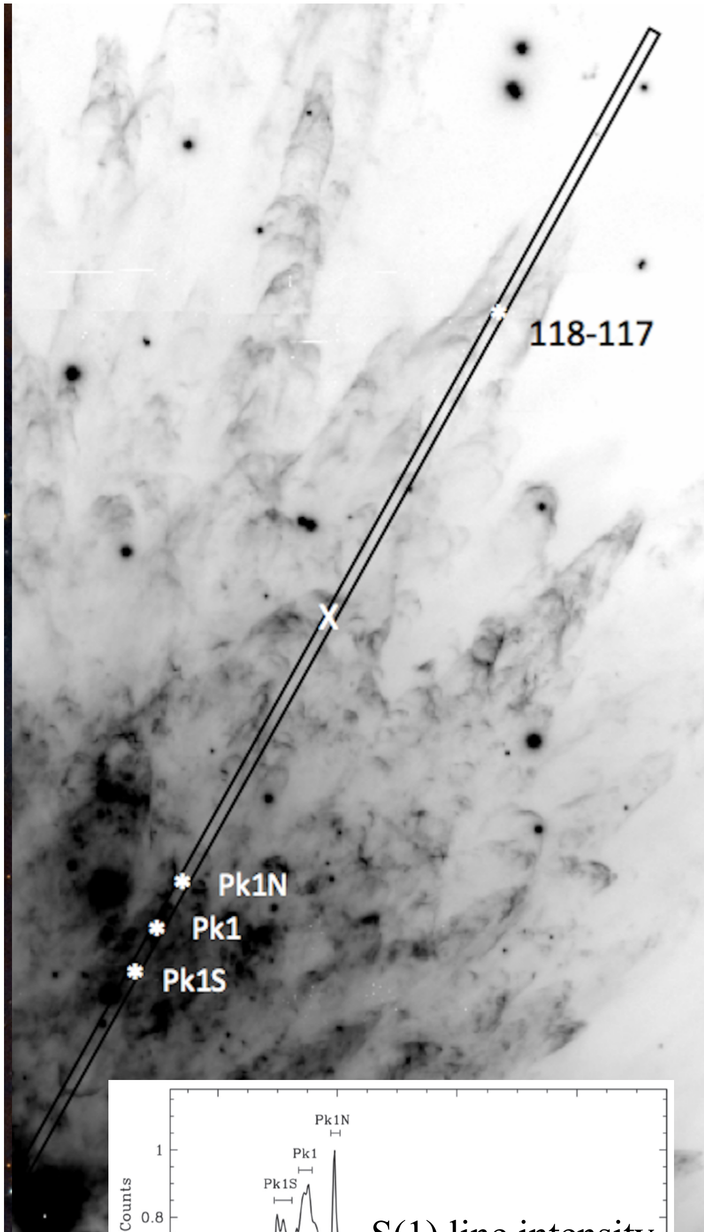
   But why would a single temperature describe this hot H_2, which one expects would cool rapidly?

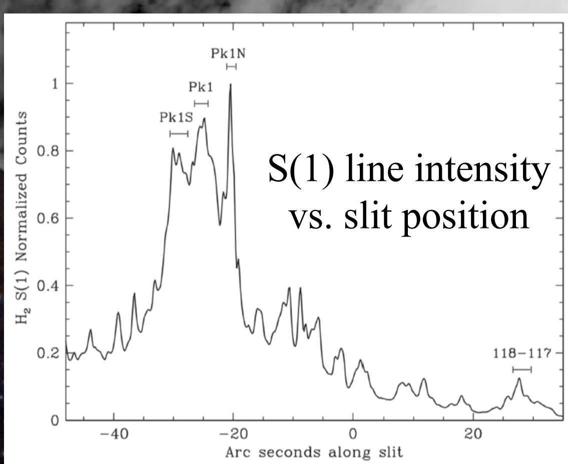
???

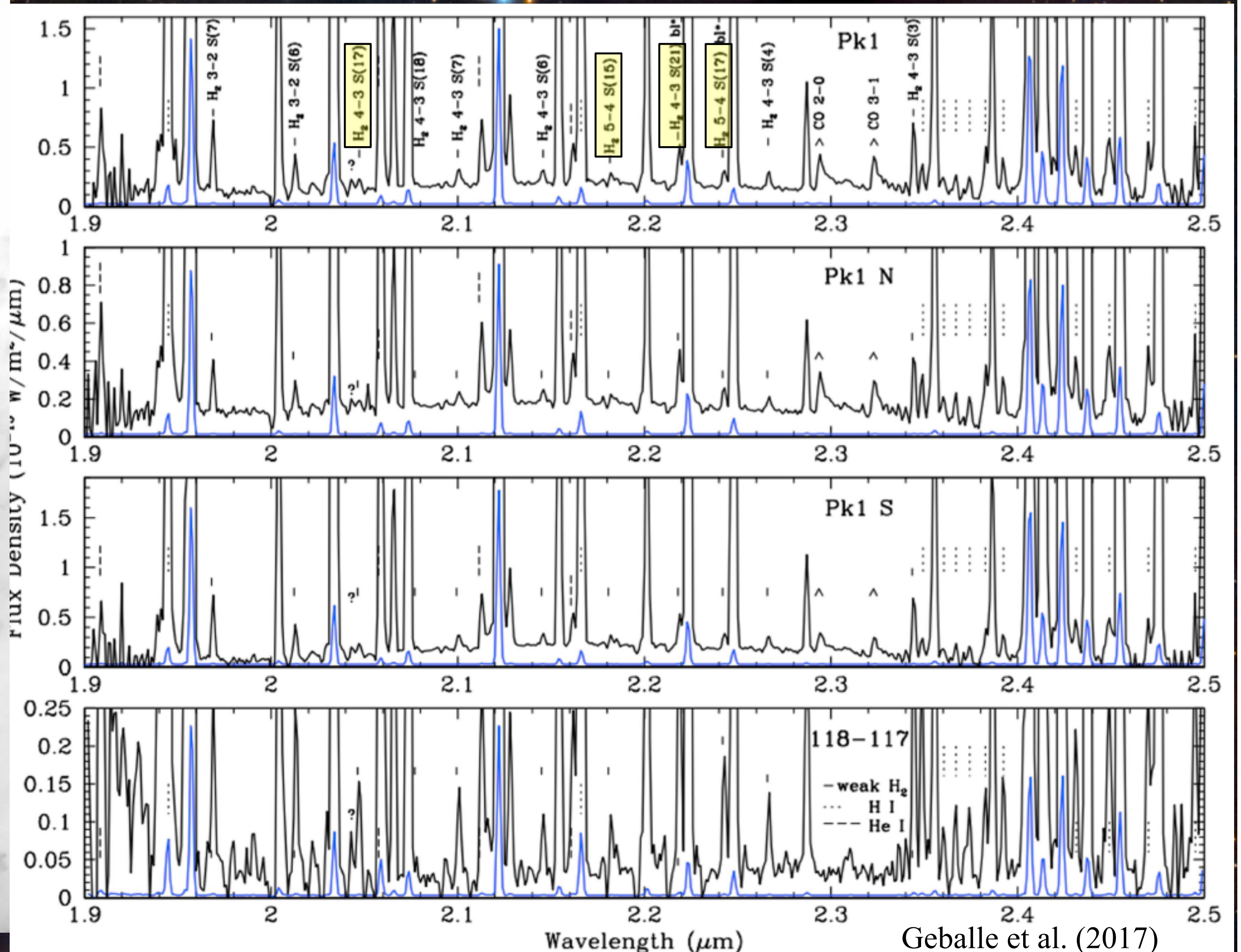
Al Howard


Is this high temperature H_2 component
present in shocked gas elsewhere?
Orion "bullets"/"fingers"
Bally et al. (2014)
Gemini S / GSAOI

Use Gemini/GNIRS in long-slit mode to sample a wide range of shocks in OMC-1



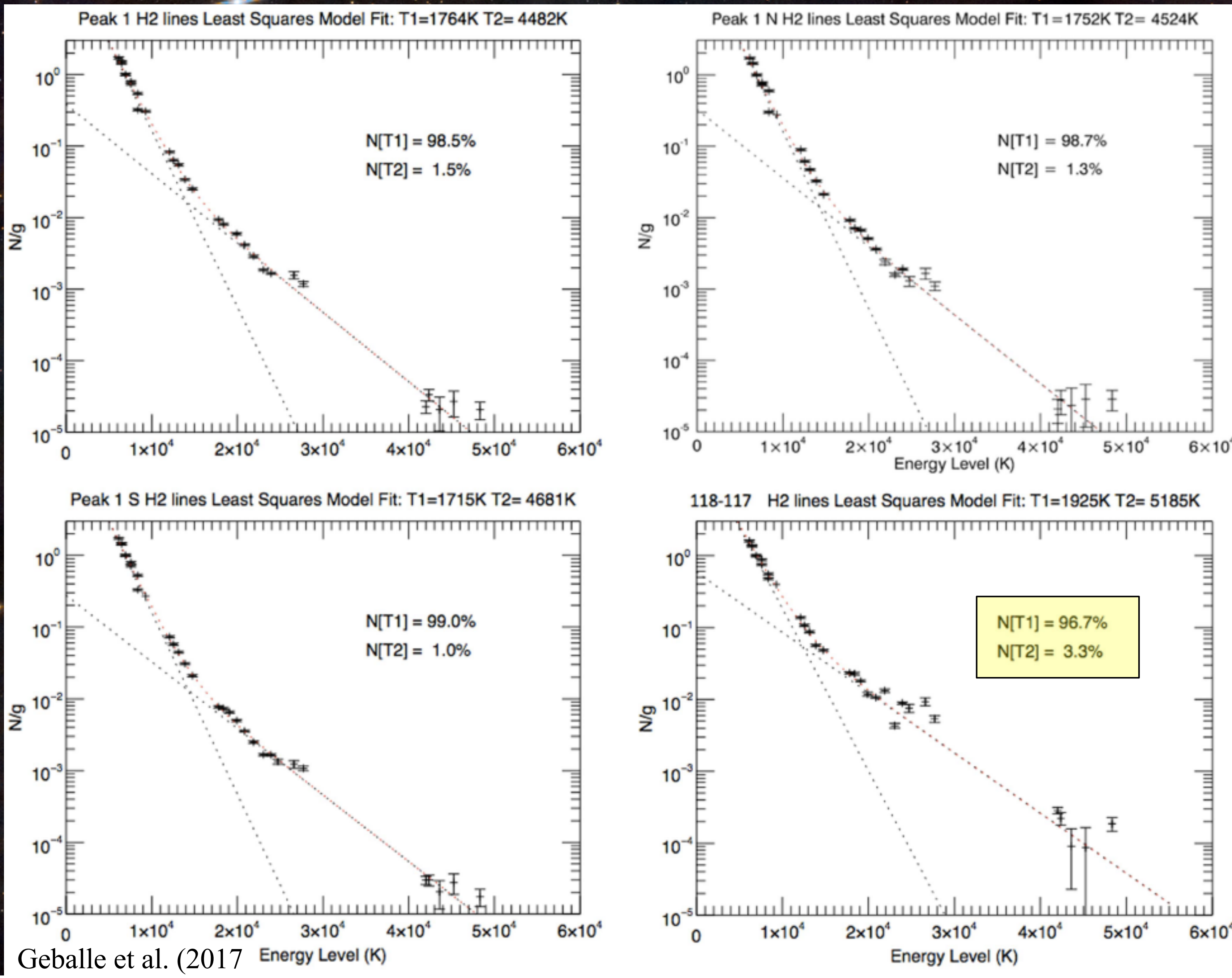




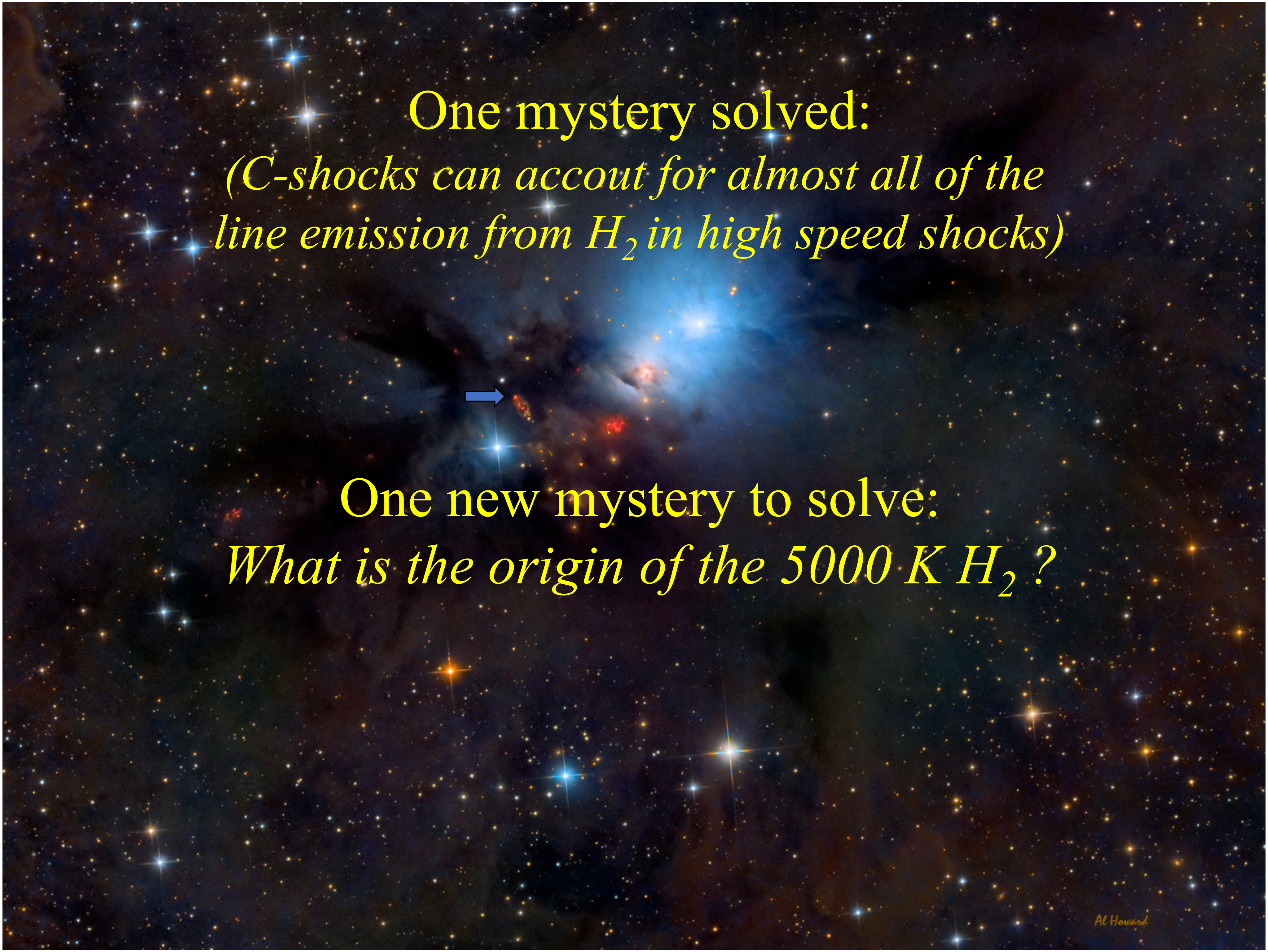
Contaminated by lines from ionized nebula and scattered line emission from BN, so fewer very high excitation (weak) lines are clearly seen.

H_2 population distributions similar to HH7

Highest pct of 5000 K (3%) gas found at tip of finger (118-117)



Geballe et al. (2017


One mystery solved:
(C-shocks can accout for almost all of the line emission from H_2 in high speed shocks)
One new mystery to solve:
What is the origin of the 5000 K H_2 ?
Al Howard