Fluorescent H_2 Emission Lines from the Reflection Nebula NGC 7023 Observed with IGRINS

Present at IGRINS workshop 2017 – Kyung Hee University

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Image from
http://www.cosmotography.com/images/lrg_ngc7023.html

Molecular Hydrogen Observations in Molecular Clouds

Iris

Horse head

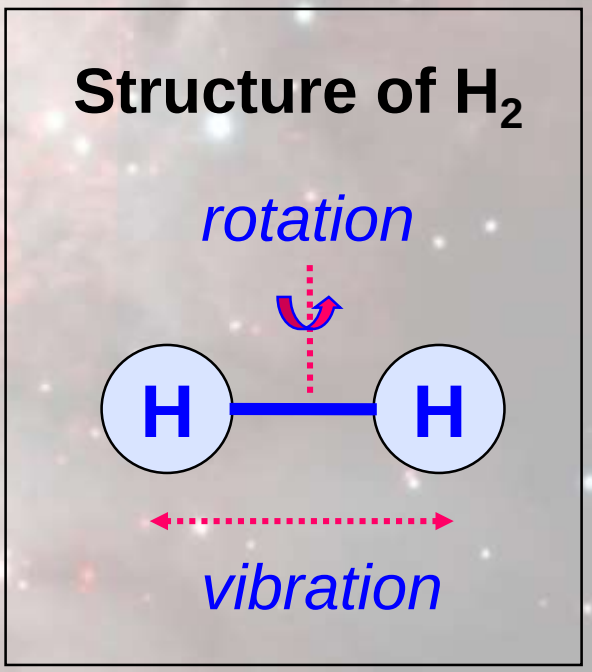
Orion

M1

Crab

Molecular Hydrogen

- The most abundant molecular
- Tracing ***interaction*** bet, the star and the cloud.
  - Shocked Region
  - Photodissociation Region



H_2 Excitation Mechanism

Thermal

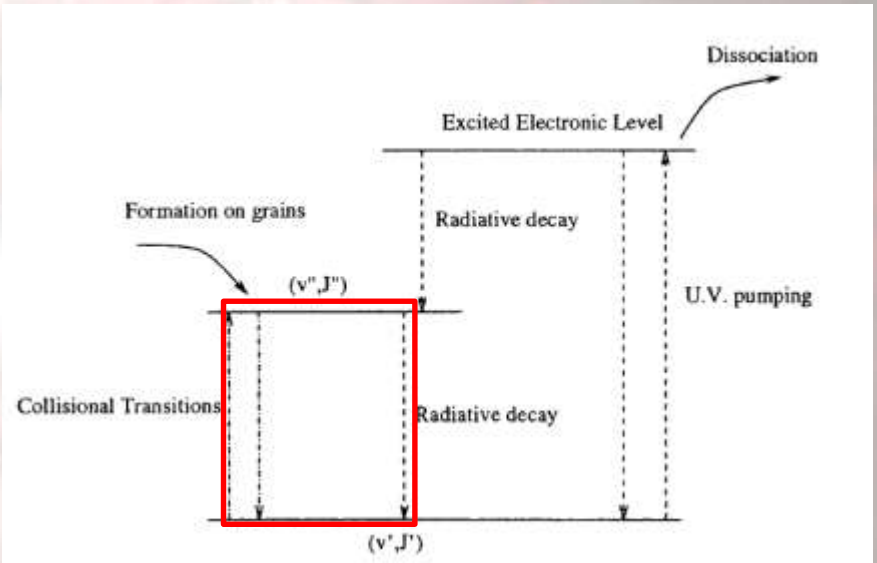
Collisional Excitation
by shock
in IR bands

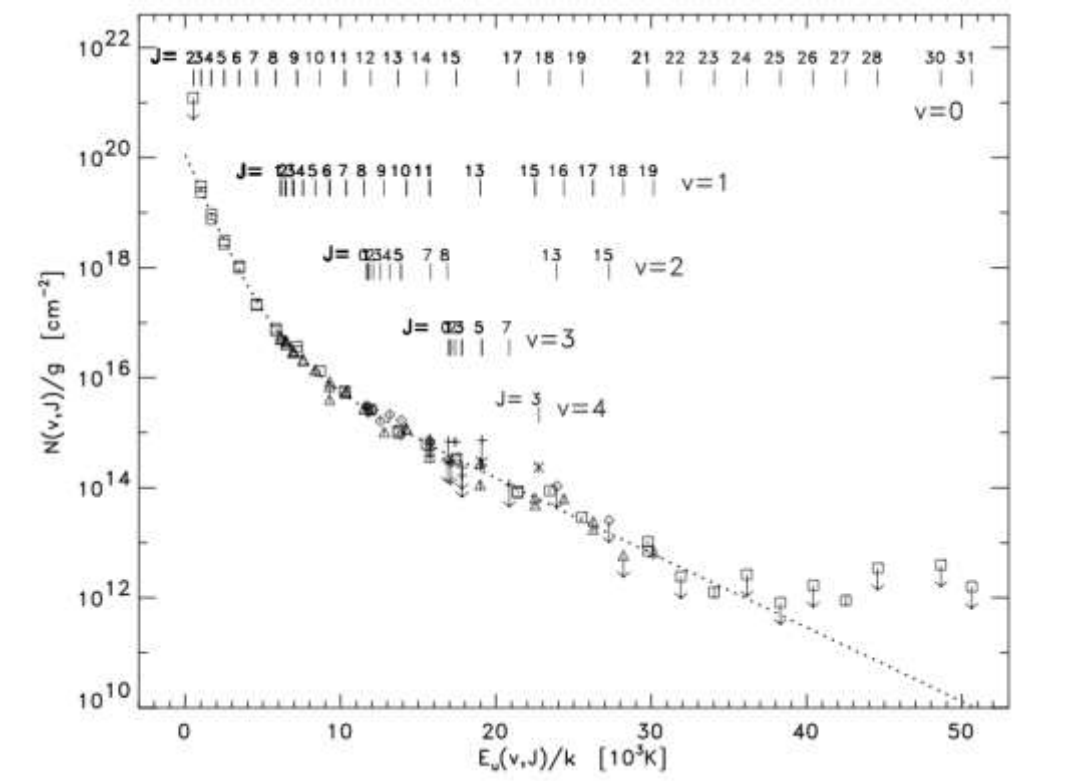
Non-Thermal

Electrically Excited
by Absorbing far-UV
and Radiates
in far-UV and IR bands

Thermal

Collisional Excitation
by shock
in IR bands

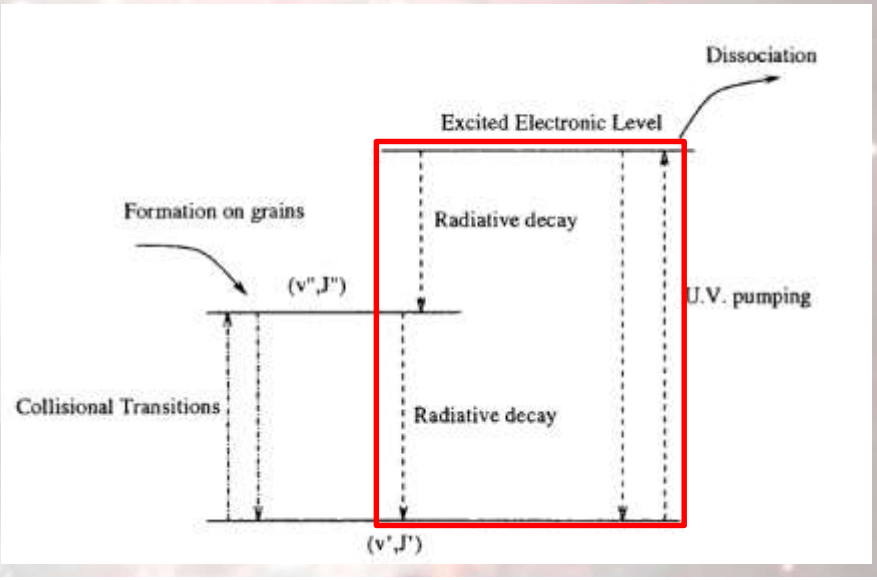


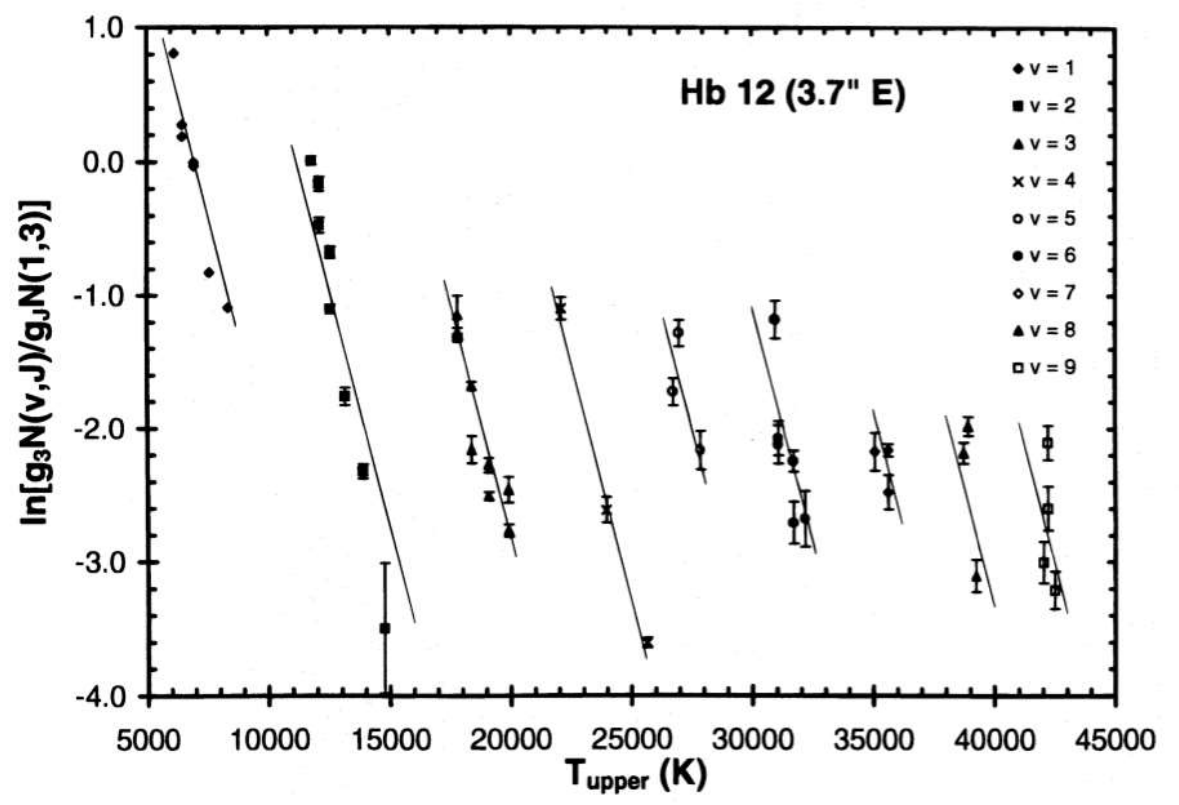


Rosenthal et al. (2000)

Non-Thermal

Electrically Excited
by Absorbing far-UV
and Radiates
in far-UV and IR bands





Hora & Latter (1996)

H_2 Excitation – Line Intensity & Ratio

Thermal by shocks	**Non-thermal** by Far-UV
Line ratio (2-1 / 1-0)	
C-shocks : ~ 0.2 **J-shocks : < 0.5** **slow J-shocks (< 24 km/s): < 0.3**	**PDR (n_{H2} < 5 x 10^4 /cm^3): ~ 0.6** **dense PDR : < 0.6**

Measured ratio = 0.3 ~ 0.5

possible mechanism:

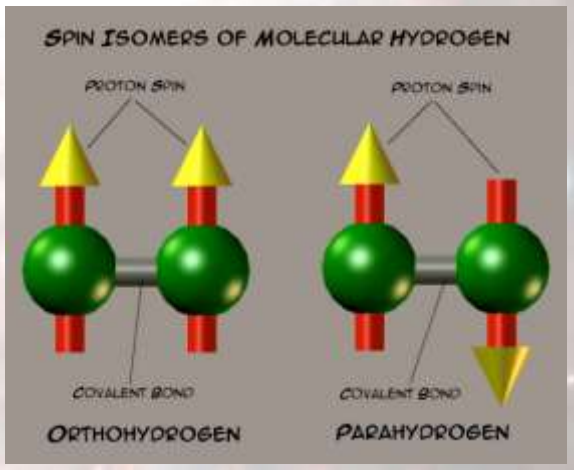
- pure dense PDR
- pure J-shocks, C+J-shocks
- PDR + shocks

H_2 Excitation – Ortho and Para Ratio

TABLE 1
Branch Notation

Branch	$J_{up}-J_{lo}$
O.....	−2
P.....	−1
Q.....	0
R.....	+1
S.....	+2

Shaw et al. (2005)



Ortho-to-para-H2 ratio (OPR)

OPR = 3

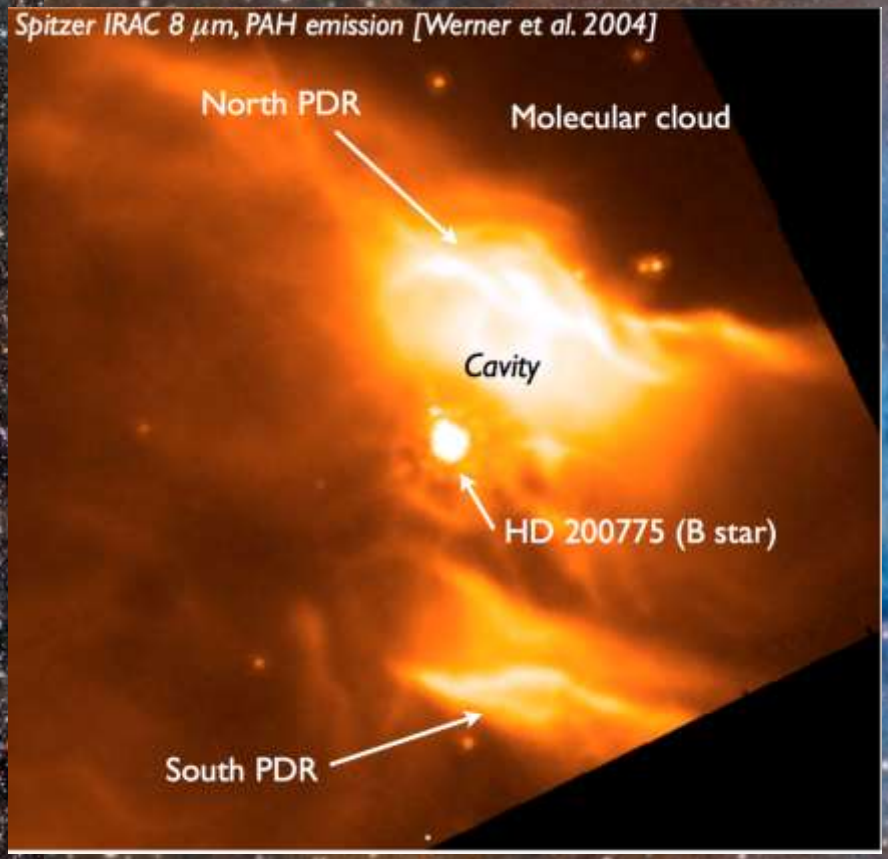
OPR < 3

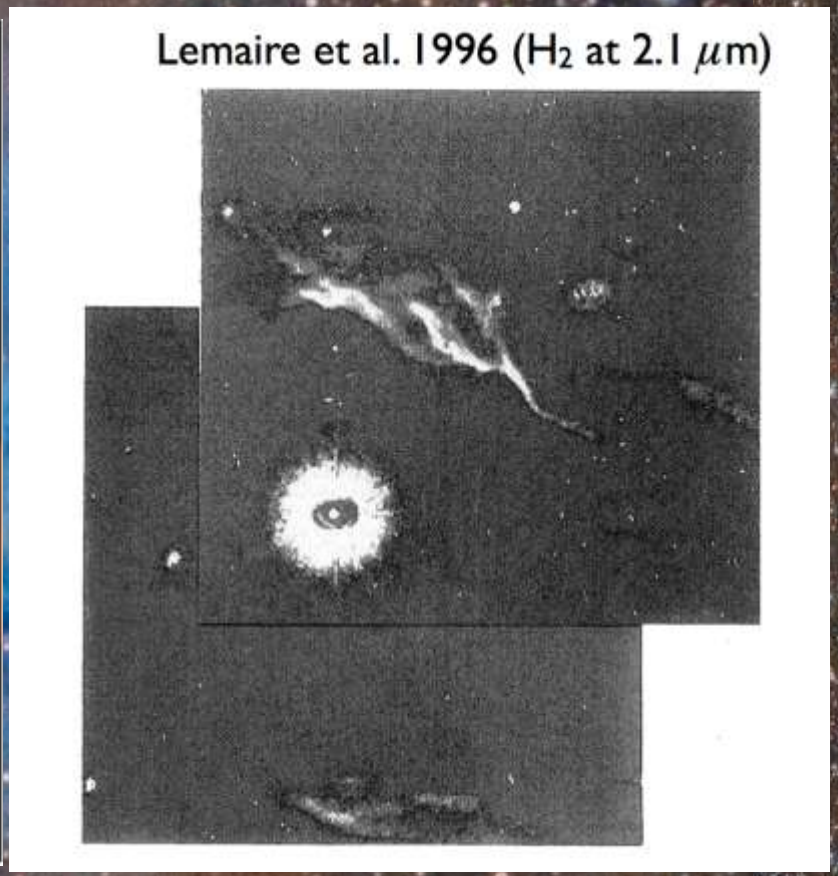
Thermal by shock

Non-thermal by Far-UV

Constellation: Cepheus

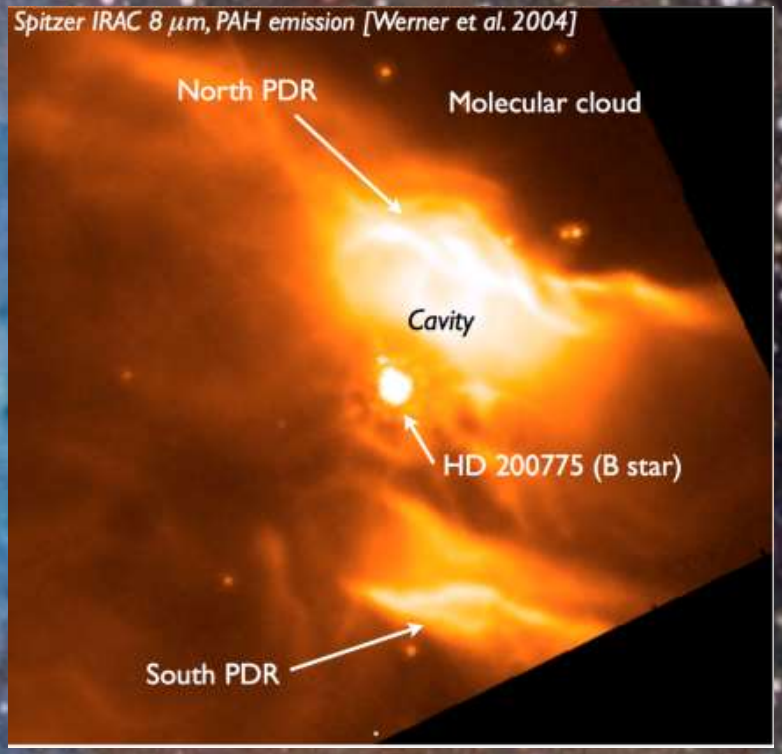
NGC 7023 (Iris Nebula)





NGC 7023 (Iris Nebula)

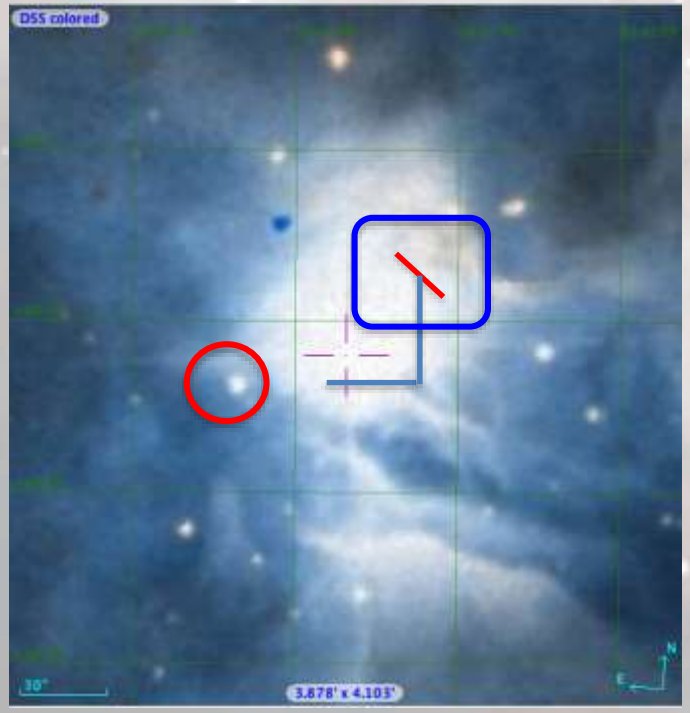
- Illuminated by HD 200775 (Herbig B3Ve-B5, T_{eff} = 17,000 K)
- PDRs in North and South from HD 200775
- D = 430 (+160/-90) pc
- Clumpy structure ? (Martini+1999;1997)
- Advancing PDR ? (Fuente +2000)
- Existing of shock ? (Fuente +2000)



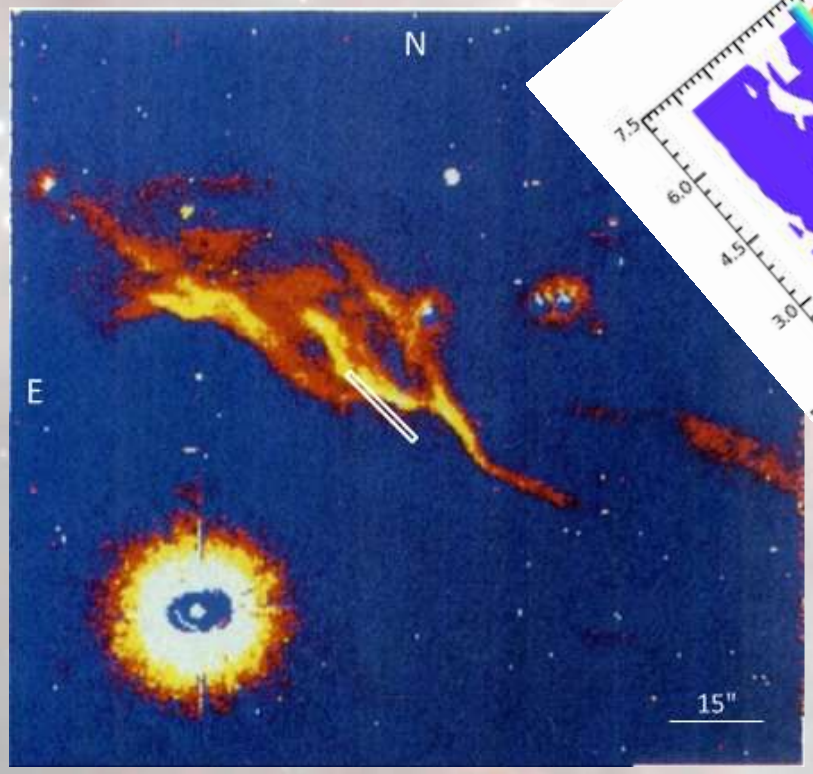
IGRINS - observations

- Target: NGC 7023
- Date: 2014 July 12 (Commissioning)
- Exposures: 2 x 600s / frame
- Positions (Ra, Dec)$_{J2000}$ = (21:01:36.9, +68:09:47.8)
- Total exposure time:

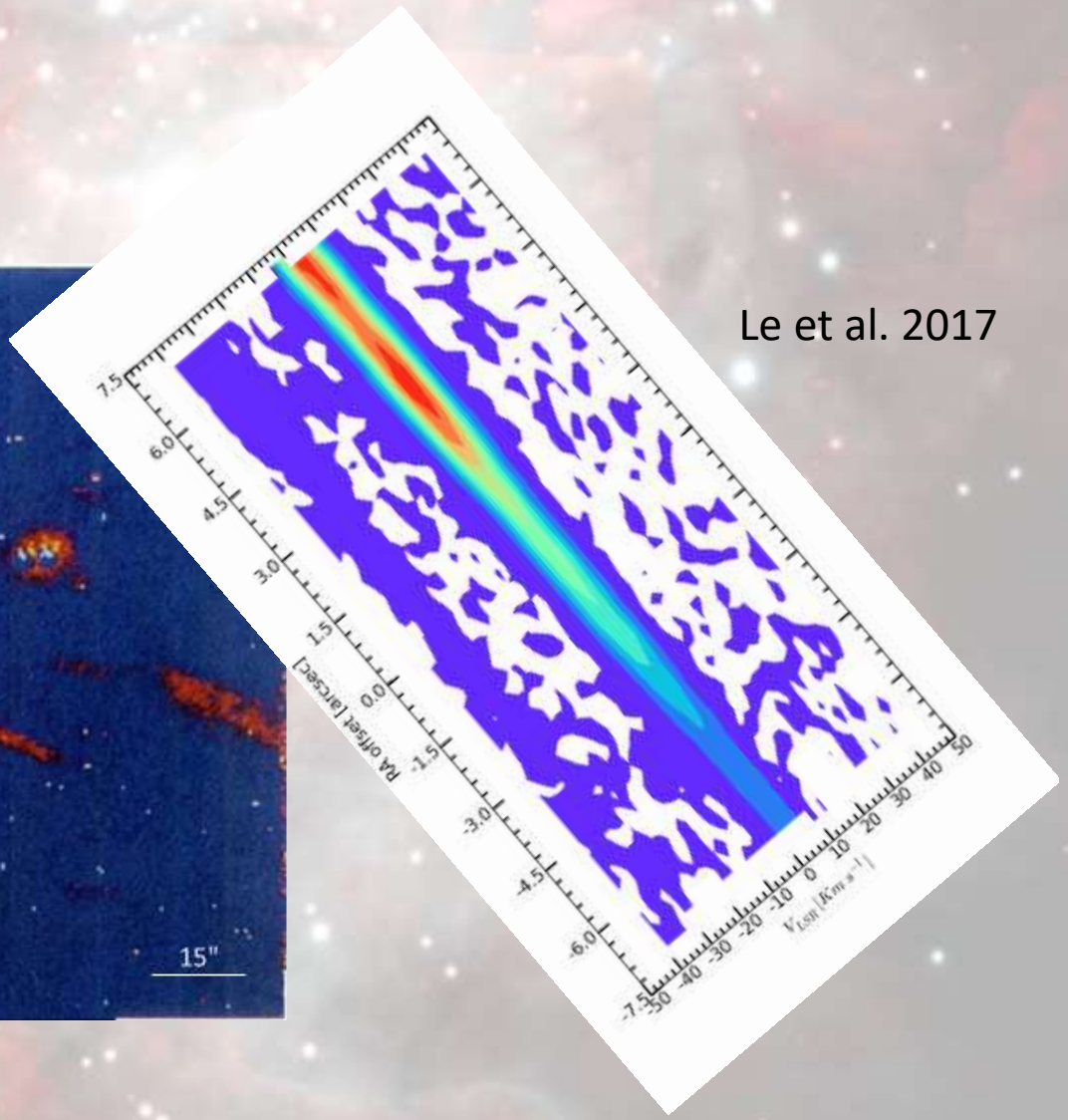
t = 1200 s, ON position



t = 1200 s, OFF position



Lemaire et al. (1996)



Le et al. 2017

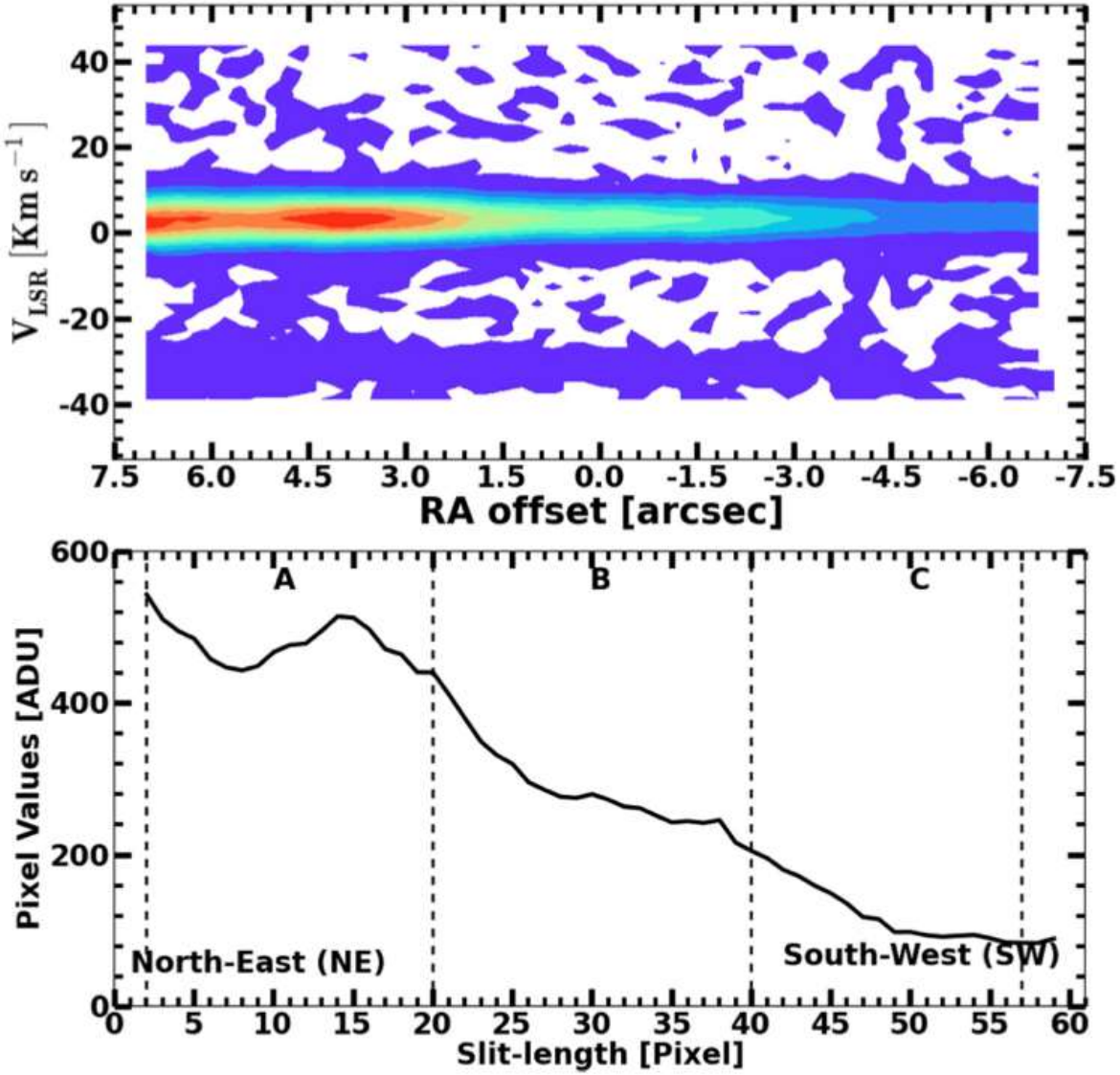
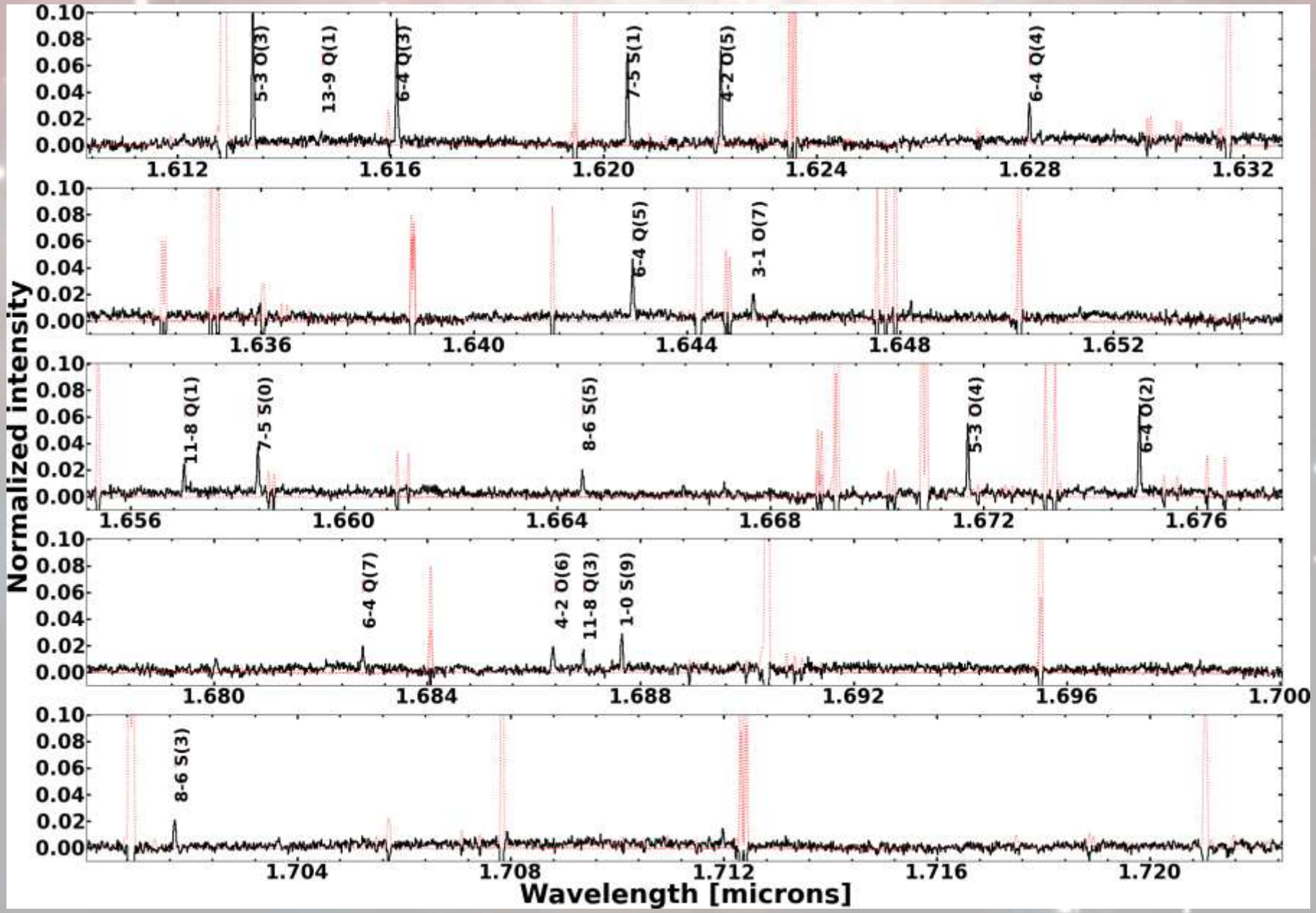


Figure 4. Radial velocity diagram of the 1-0 S(1) line (top plot). In the diagram, $1'' = 3.66$ pixels. The bottom plot shows the intensity profile at the peak of the 1-0 S(1) line. The black dashed lines show the separated regions A, B, and C along the slit length.

H_2 spectra


Normalized intensity
Wavelength [microns]
5-3 O(3)
13-9 Q(1)
6-4 Q(3)
7-5 S(1)
4-2 O(5)
6-4 Q(4)
6-4 Q(5)
3-1 O(7)
11-8 Q(1)
7-5 S(0)
8-6 S(5)
5-3 O(4)
6-4 O(2)
6-4 Q(7)
4-2 O(6)
11-8 Q(3)
1-0 S(9)
8-6 S(3)

H_2 spectra

- 68 H_2 rovibrational emission lines
  (v = 1 – 13 and J = 1 – 11)
  from Regions A, B, and C

Table 1
NGC 7023 H_2 Line Observation

		Region A			Region B			Region C		
Line	λ[a]	I[b]	f[c]	$\ln(N_u/g)$[d]	I[b]	f[c]	$\ln(N_u/g)$[d]	I[b]	f[c]	$\ln(N_u/g)$[d]
4-2 Q(9)	1.498884	0.863(0.107)	0.041(0.005)	27.867(0.124)	···	···	···	···	···	···
4-2 O(3)	1.509865	5.782(0.311)	0.275(0.015)	31.156(0.054)	4.432(0.269)	0.372(0.024)	30.890(0.061)	2.731(0.224)	0.511(0.044)	30.406(0.082)
5-3 Q(4)	1.515792	2.356(0.229)	0.112(0.011)	30.306(0.097)	1.737(0.168)	0.146(0.014)	30.001(0.096)	···	···	···
3-1 O(5)	1.522026	2.920(0.188)	0.139(0.009)	30.990(0.064)	2.271(0.172)	0.190(0.015)	30.739(0.076)	2.022(0.212)	0.378(0.041)	30.623(0.105)
5-3 Q(5)	1.528641	2.562(0.199)	0.122(0.010)	29.125(0.078)	2.251(0.186)	0.189(0.016)	28.996(0.083)	1.320(0.131)	0.247(0.025)	28.462(0.099)
6-4 S(0)	1.536908	1.942(0.150)	0.092(0.007)	30.600(0.077)	2.134(0.156)	0.179(0.013)	30.694(0.073)	···	···	···
10-7 O(3)	1.548851	1.039(0.111)	0.049(0.005)	29.146(0.106)	0.893(0.102)	0.075(0.009)	28.995(0.114)	0.488(0.072)	0.091(0.014)	28.390(0.148)
5-3 O(2)	1.560730	2.524(0.169)	0.120(0.008)	31.481(0.067)	1.876(0.138)	0.157(0.012)	31.184(0.073)	1.113(0.114)	0.208(0.022)	30.662(0.103)
5-3 Q(7)	1.562627	1.578(0.120)	0.075(0.006)	28.402(0.076)	1.285(0.098)	0.108(0.008)	28.196(0.076)	···	···	···
4-2 O(4)	1.563516	2.546(0.160)	0.121(0.008)	31.355(0.063)	2.340(0.139)	0.196(0.012)	31.271(0.059)	1.311(0.110)	0.245(0.022)	30.692(0.084)
7-5 S(2)	1.588290	1.240(0.113)	0.059(0.005)	29.124(0.091)	0.973(0.097)	0.082(0.008)	28.881(0.100)	0.860(···)	0.161(···)	28.758(···)
6-4 Q(1)	1.601535	3.992(0.193)	0.190(0.010)	30.248(0.048)	3.369(0.173)	0.283(0.015)	30.078(0.051)	2.222(0.134)	0.416(0.028)	29.662(0.060)
6-4 Q(2)	1.607386	3.813(0.194)	0.182(0.010)	31.136(0.051)	2.255(0.157)	0.189(0.014)	30.611(0.070)	1.600(0.138)	0.299(0.027)	30.268(0.086)
5-3 O(3)	1.613536	4.932(0.237)	0.235(0.012)	30.697(0.048)	4.112(0.214)	0.345(0.019)	30.515(0.052)	2.549(0.165)	0.477(0.034)	30.037(0.065)
13-9 Q(1)	1.614812	0.247(0.057)	0.012(0.003)	28.383(0.233)	···	···	···	···	···	···
6-4 Q(3)	1.616211	2.879(0.158)	0.137(0.008)	29.505(0.055)	2.353(0.136)	0.197(0.012)	29.303(0.058)	1.673(0.116)	0.313(0.023)	28.963(0.069)
7-5 S(1)	1.620530	2.723(0.145)	0.130(0.007)	29.208(0.053)	2.283(0.143)	0.191(0.013)	29.032(0.063)	1.098(0.116)	0.205(0.022)	28.300(0.106)
4-2 O(5)	1.622292	3.133(0.162)	0.149(0.008)	30.507(0.052)	2.716(0.154)	0.228(0.014)	30.364(0.057)	1.914(0.143)	0.358(0.029)	30.014(0.075)
6-4 Q(4)	1.628084	0.982(0.098)	0.047(0.005)	29.325(0.100)	0.718(0.093)	0.060(0.008)	29.012(0.129)	0.492(0.074)	0.092(0.014)	28.634(0.151)
6-4 Q(5)	1.643080	1.858(0.129)	0.088(0.006)	28.703(0.070)	1.425(0.115)	0.119(0.010)	28.438(0.081)	0.832(0.084)	0.156(0.016)	27.900(0.101)
3-1 O(7)	1.645324	0.668(0.068)	0.032(0.003)	29.871(0.102)	0.615(0.065)	0.052(0.006)	29.789(0.106)	0.353(0.051)	0.066(0.010)	29.233(0.145)
11-8 Q(1)	1.657105	0.730(0.083)	0.035(0.004)	28.851(0.114)	0.570(0.075)	0.048(0.006)	28.604(0.131)	0.545(0.066)	0.102(0.013)	28.558(0.122)
7-5 S(0)	1.658482	1.054(0.087)	0.050(0.004)	30.020(0.083)	0.818(0.095)	0.069(0.008)	29.767(0.116)	···	···	···
8-6 S(5)	1.664578	0.518(0.075)	0.025(0.004)	26.994(0.144)	···	···	···	···	···	···
5-3 O(4)	1.671821	1.999(0.138)	0.095(0.007)	30.793(0.069)	1.372(0.114)	0.115(0.010)	30.417(0.083)	1.382(0.107)	0.259(0.021)	30.424(0.077)
6-4 O(2)	1.675019	2.127(0.128)	0.101(0.006)	31.167(0.060)	1.451(0.102)	0.122(0.009)	30.784(0.071)	1.125(···)	0.211(···)	30.530(···)
4-2 O(6)	1.686494	0.791(0.085)	0.038(0.004)	30.350(0.108)	···	···	···	···	···	···
1-0 S(9)	1.687721	1.017(0.108)	0.048(0.005)	29.014(0.106)	0.610(0.081)	0.051(0.007)	28.504(0.133)	0.205(0.045)	0.038(0.008)	27.415(0.218)
8-6 S(3)	1.701797	1.005(0.099)	0.048(0.005)	27.806(0.098)	0.846(0.093)	0.071(0.008)	27.635(0.110)	0.453(0.068)	0.085(0.013)	27.010(0.150)
7-5 Q(1)	1.728779	3.613(0.211)	0.172(0.010)	30.150(0.058)	2.836(0.207)	0.238(0.018)	29.907(0.073)	2.394(0.129)	0.448(0.027)	29.738(0.054)
6-4 O(3)	1.732637	4.227(0.233)	0.201(0.011)	30.382(0.055)	3.519(0.212)	0.295(0.019)	30.199(0.060)	1.776(0.129)	0.332(0.026)	29.515(0.073)
5-3 O(5)	1.735888	3.222(0.159)	0.153(0.008)	30.194(0.049)	2.298(0.154)	0.193(0.013)	29.856(0.067)	···	···	···
1-0 S(7)	1.748035	3.624(0.218)	0.173(0.011)	29.937(0.060)	2.475(0.204)	0.208(0.018)	29.555(0.082)	···	···	···
4-2 O(7)	1.756296	0.873(0.091)	0.042(0.004)	29.527(0.105)	0.645(0.070)	0.054(0.006)	29.225(0.108)	0.351(0.052)	0.066(0.010)	28.617(0.148)
11-8 O(3)	1.760929	0.940(0.100)	0.045(0.005)	29.124(0.106)	···	···	···	···	···	···
7-5 O(5)	2.022040	1.022(0.078)	0.049(0.004)	28.774(0.076)	0.972(0.073)	0.082(0.006)	28.724(0.075)	0.247(0.031)	0.046(0.006)	27.356(0.124)
6-4 O(7)	2.029694	0.415(0.043)	0.020(0.002)	28.161(0.104)	···	···	···	···	···	···
1-0 S(2)	2.033756	9.052(0.224)	0.431(0.012)	32.560(0.025)	5.579(0.174)	0.468(0.017)	32.076(0.031)	2.795(0.118)	0.523(0.026)	31.385(0.042)
8-6 O(3)	2.041816	1.613(0.113)	0.077(0.005)	29.450(0.070)	1.436(0.103)	0.120(0.009)	29.333(0.072)	0.835(0.077)	0.156(0.015)	28.790(0.093)
3-2 S(5)	2.065557	1.335(0.096)	0.064(0.005)	28.924(0.072)	0.971(0.078)	0.081(0.007)	28.606(0.081)	0.518(0.049)	0.097(0.010)	27.978(0.095)
12-9 O(3)	2.069969	0.311(0.037)	0.015(0.002)	28.392(0.118)	0.289(0.035)	0.024(0.003)	28.321(0.122)	···	···	···
2-1 S(3)	2.073510	7.288(0.179)	0.347(0.010)	30.693(0.025)	4.718(0.141)	0.396(0.014)	30.258(0.030)	2.258(0.109)	0.423(0.023)	29.521(0.048)
9-7 Q(3)	2.100659	0.387(0.034)	0.018(0.002)	27.915(0.088)	···	···	···	···	···	···
8-6 O(4)	2.121570	0.610(0.044)	0.029(0.002)	29.429(0.072)	0.540(0.045)	0.045(0.004)	29.307(0.083)	0.220(0.025)	0.041(0.005)	28.409(0.114)
1-0 S(1)	2.121831	21.002(0.291)	1.000	32.734(0.014)	11.924(0.219)	1.000	32.168(0.018)	5.343(0.146)	1.000	31.366(0.027)
2-1 S(2)	2.154225	4.197(0.137)	0.200(0.007)	31.509(0.033)	2.683(0.114)	0.225(0.010)	31.061(0.043)	1.388(0.081)	0.260(0.017)	30.402(0.058)
9-7 O(2)	2.172704	0.317(0.035)	0.015(0.002)	29.556(0.109)	0.341(0.032)	0.029(0.003)	29.627(0.095)	0.079(0.012)	0.015(0.002)	28.169(0.156)

Analysis

- Dynamical Information from H_2 Lines
- Emission line ratios
- Ortho-to-para ratios
- H_2 level population

De-convolution of Line Width

	V	ΔV_{FWHM}
Region A	3.64 ± 0.16	4.63 ± 0.34
Region B	3.46 ± 0.11	3.29 ± 0.26
Region C	3.39 ± 0.22	3.20 ± 0.27

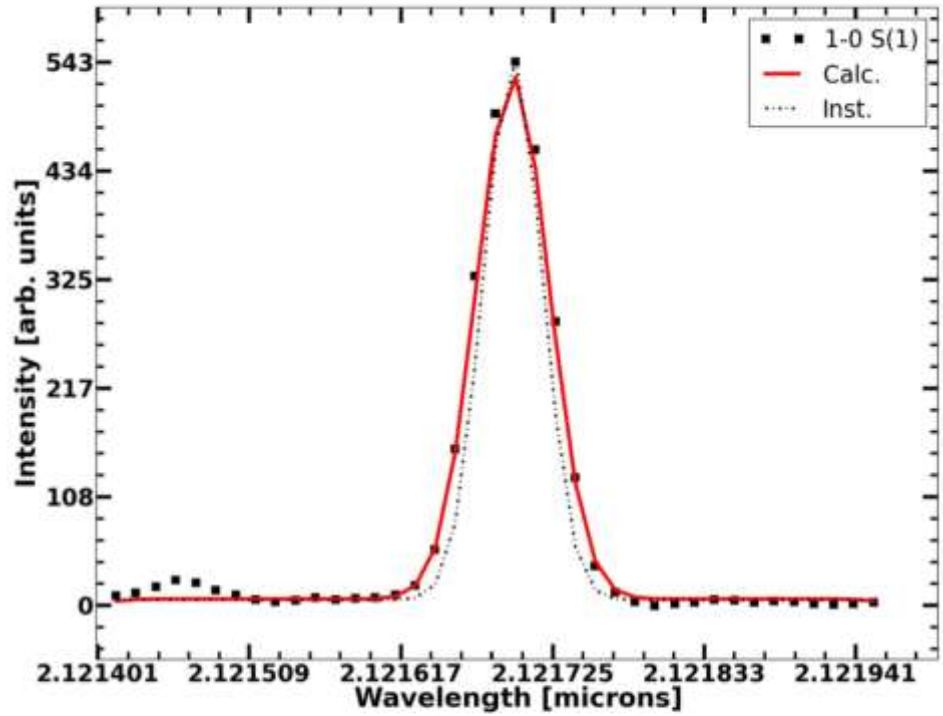


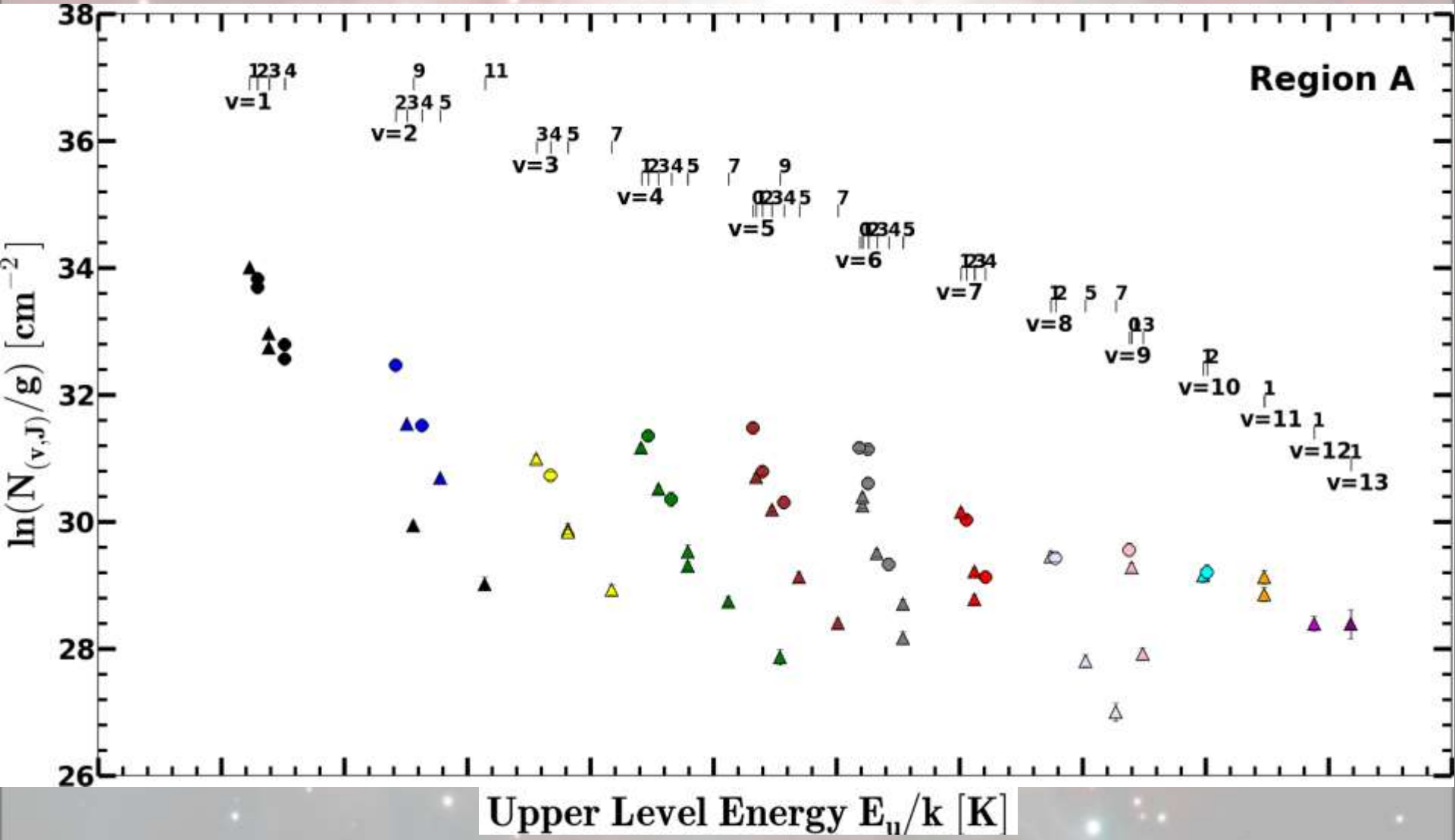
Figure 5. Observed H_2 1-0 S(1) line profile from region A in black squares. The black dotted points present the instrument profile. The solid red line is from the convolution of the instrument profile and the derived intrinsic line width.

Sample Spectra: H_2 1-0 S(1)

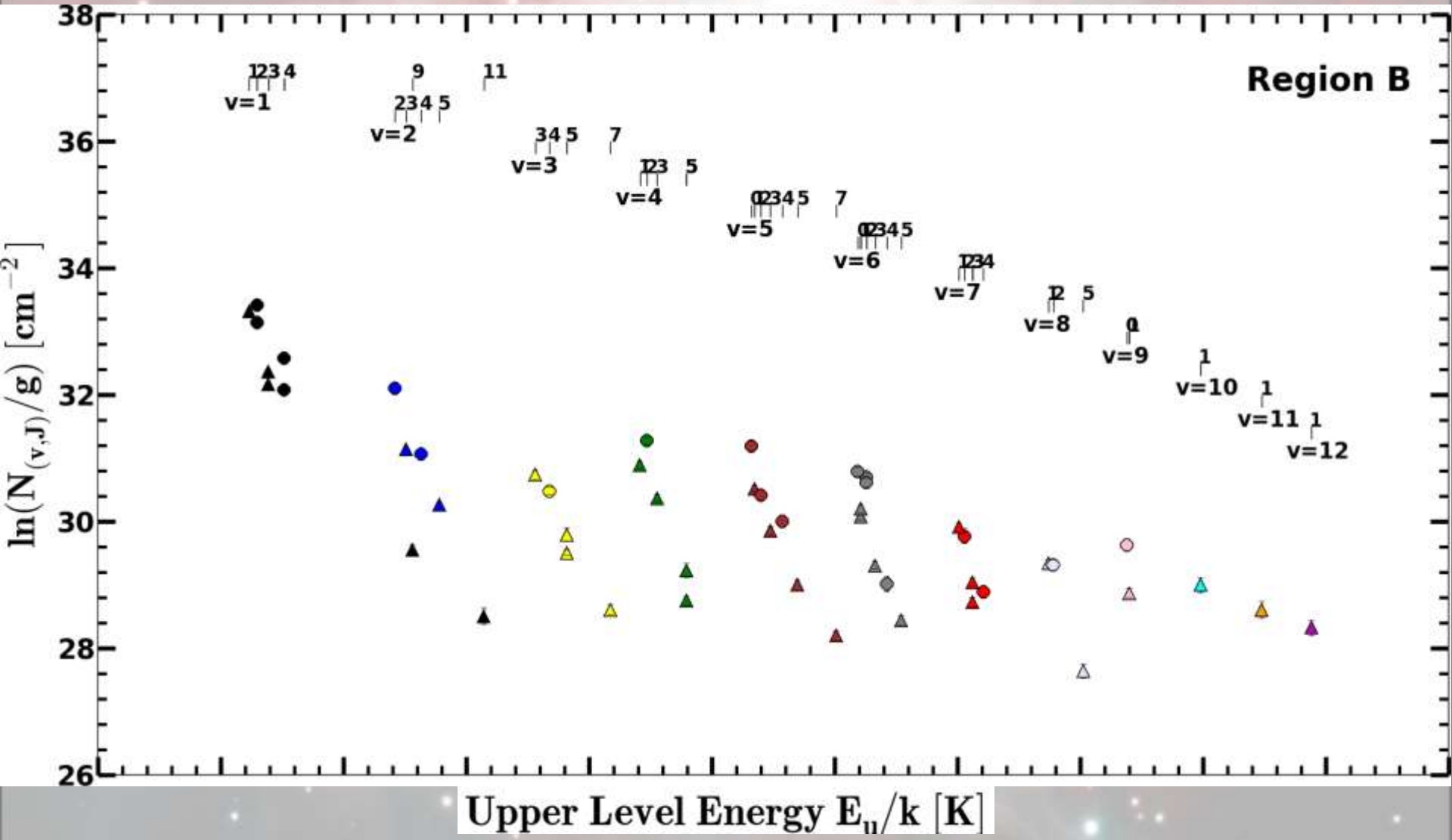
Line Analysis

	2-1 S(1) / 1-0 S(1)	Ortho-to-Para Ratio (OPR)
Region A	0.41 ± 0.01	1.82 ± 0.11
Region B	0.48 ± 0.02	1.75 ± 0.09
Region C	0.56 ± 0.03	1.63 ± 0.12

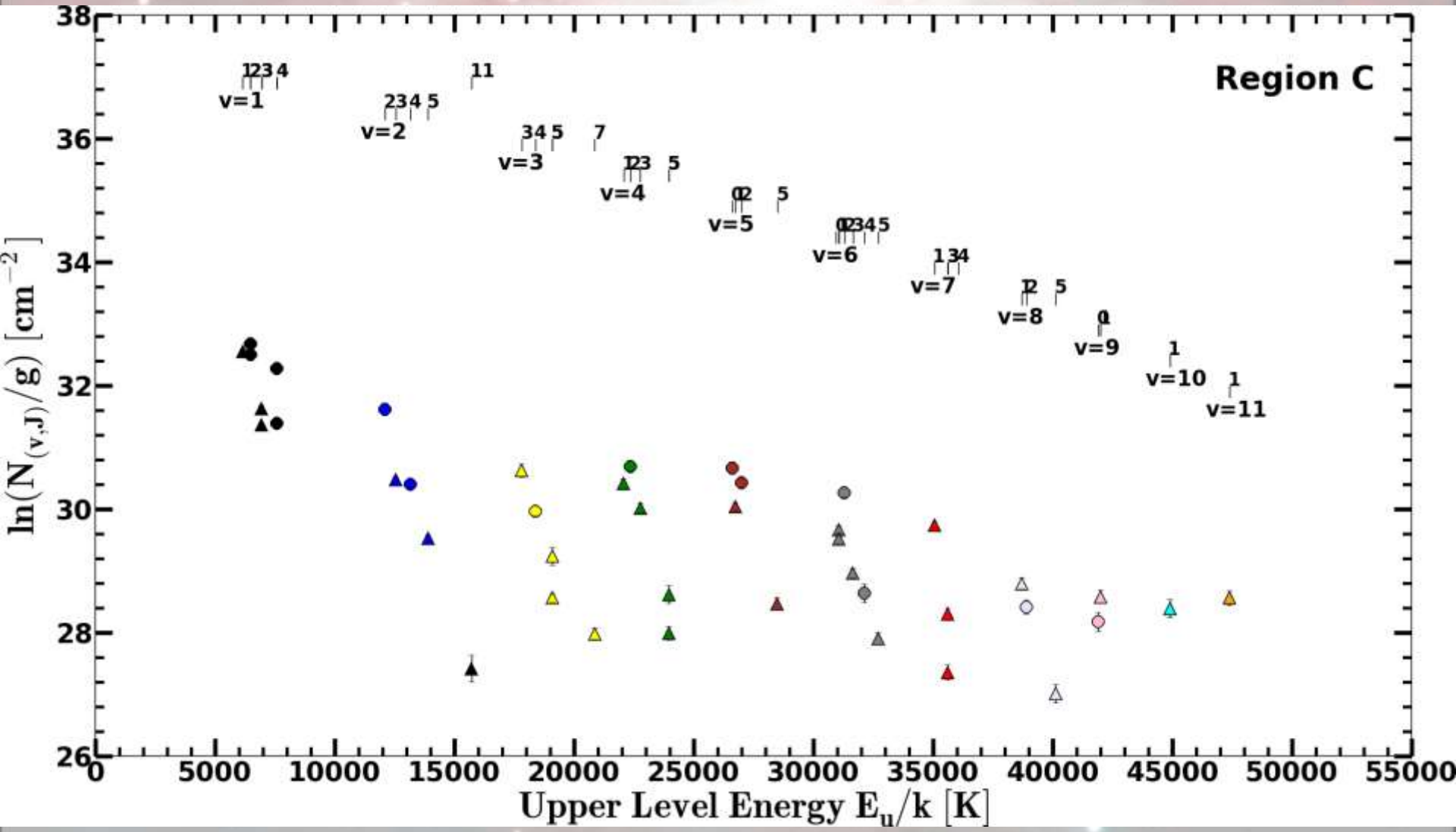
Exc. Diag. of H_2 level Column Density: ***Region A***



Exc. Diag. of H_2 level Column Density: ***Region B***



Exc. Diag. of H_2 level Column Density: ***Region C***



Comparison Data to PDR Model

Table 4
Gas Density from Comparison of the Line Ratios with the PDR Model of Draine & Bertoldi (1996)

Model	n_H (cm^{-3})	UV field strength [Habing]	χ^{2a}	χ^{2b}	χ^{2c}
aw3o	10^2	1	77	23	29
bw3d	10^2	10	91	26	31
Bw3o	10^3	10	86	25	30
Cw3o	10^3	10^2	52	16	26
Gw3o	10^4	10^2	25	15	26
Hw3o	10^4	10^3	26	17	27
Lw3o	10^5	10^3	32	38	39
Mw3o	10^5	10^4	57	53	48
Qw3o	10^6	10^4	75	85	63

Notes.
[a] χ^2 of region A.
[b] χ^2 of region B.
[c] χ^2 of region C.

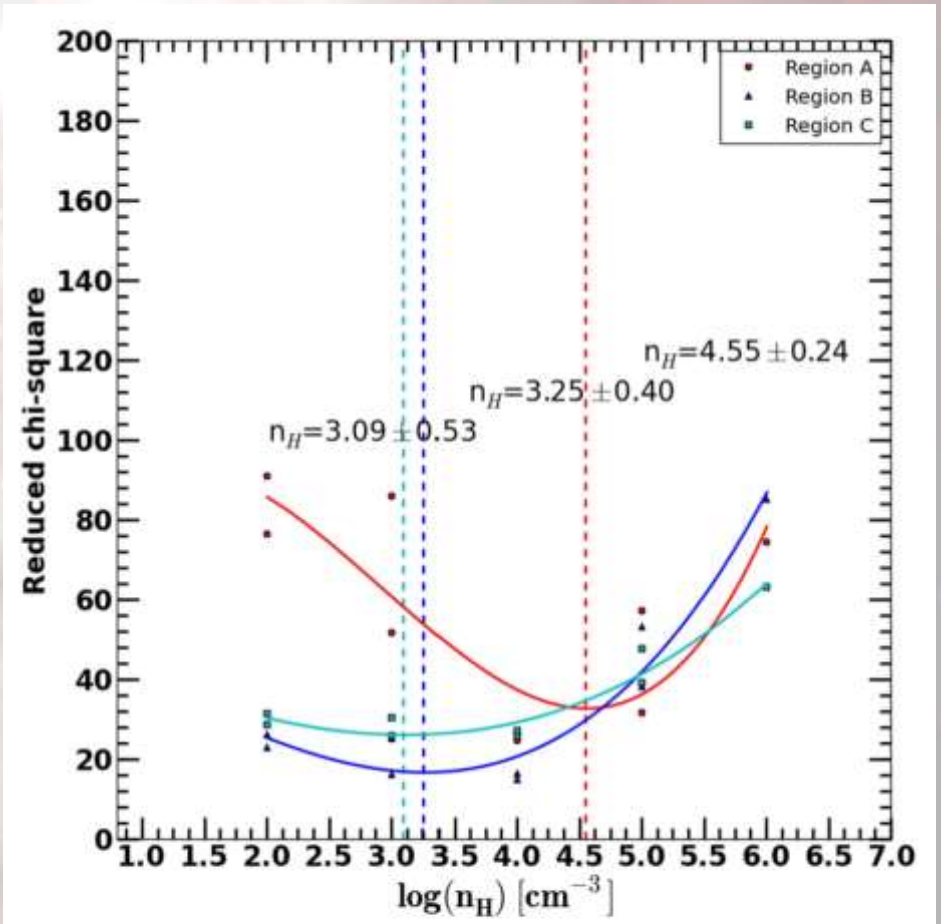
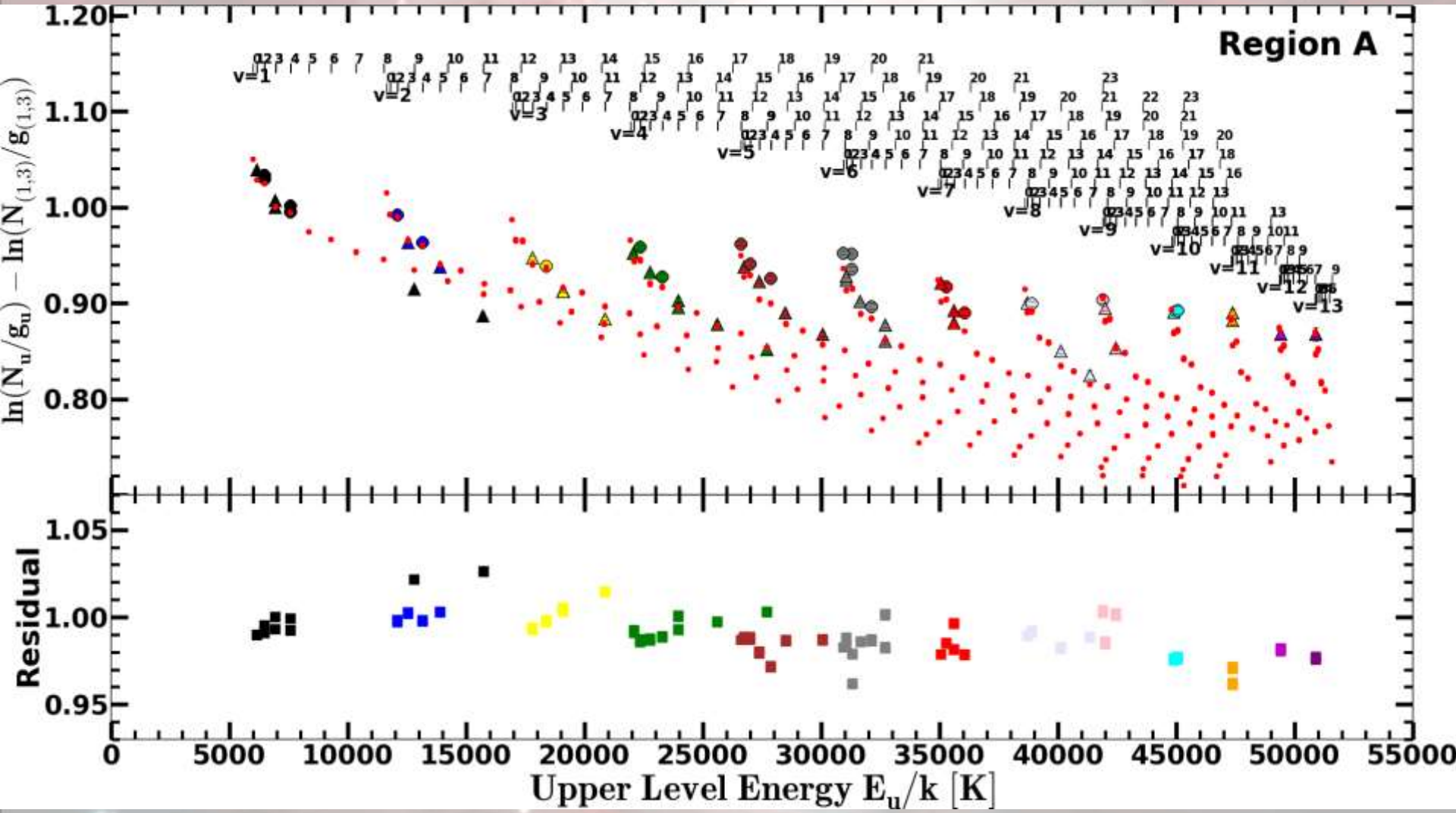
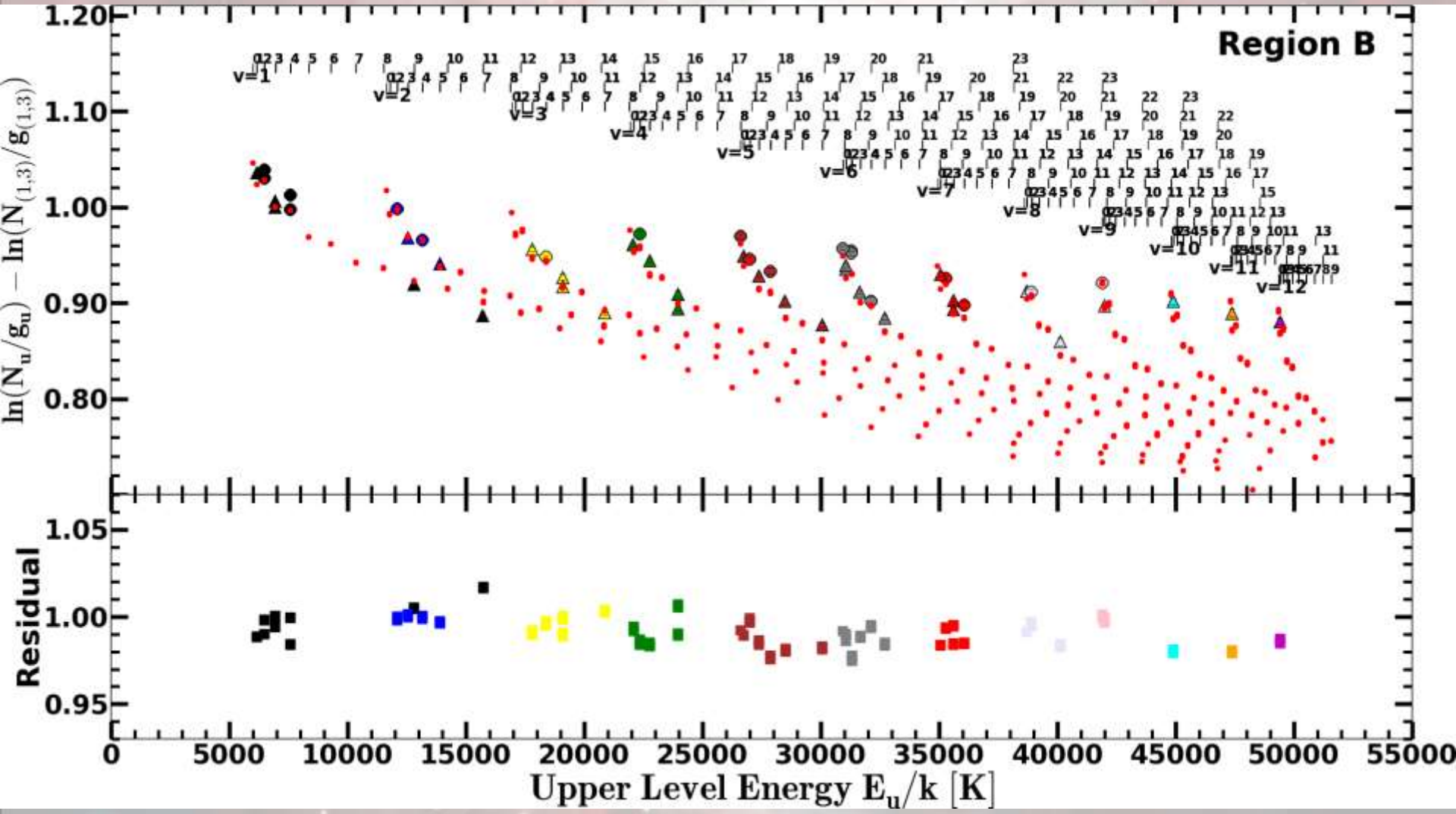


Figure 8. Estimated densities of regions A (red), B (blue), and C (cyan) from DB96. The solid lines display the fitting of reduced chi-squared values of regions A, B, and C. The dashed lines show the minimum reduced chi-squared values from the fitting.

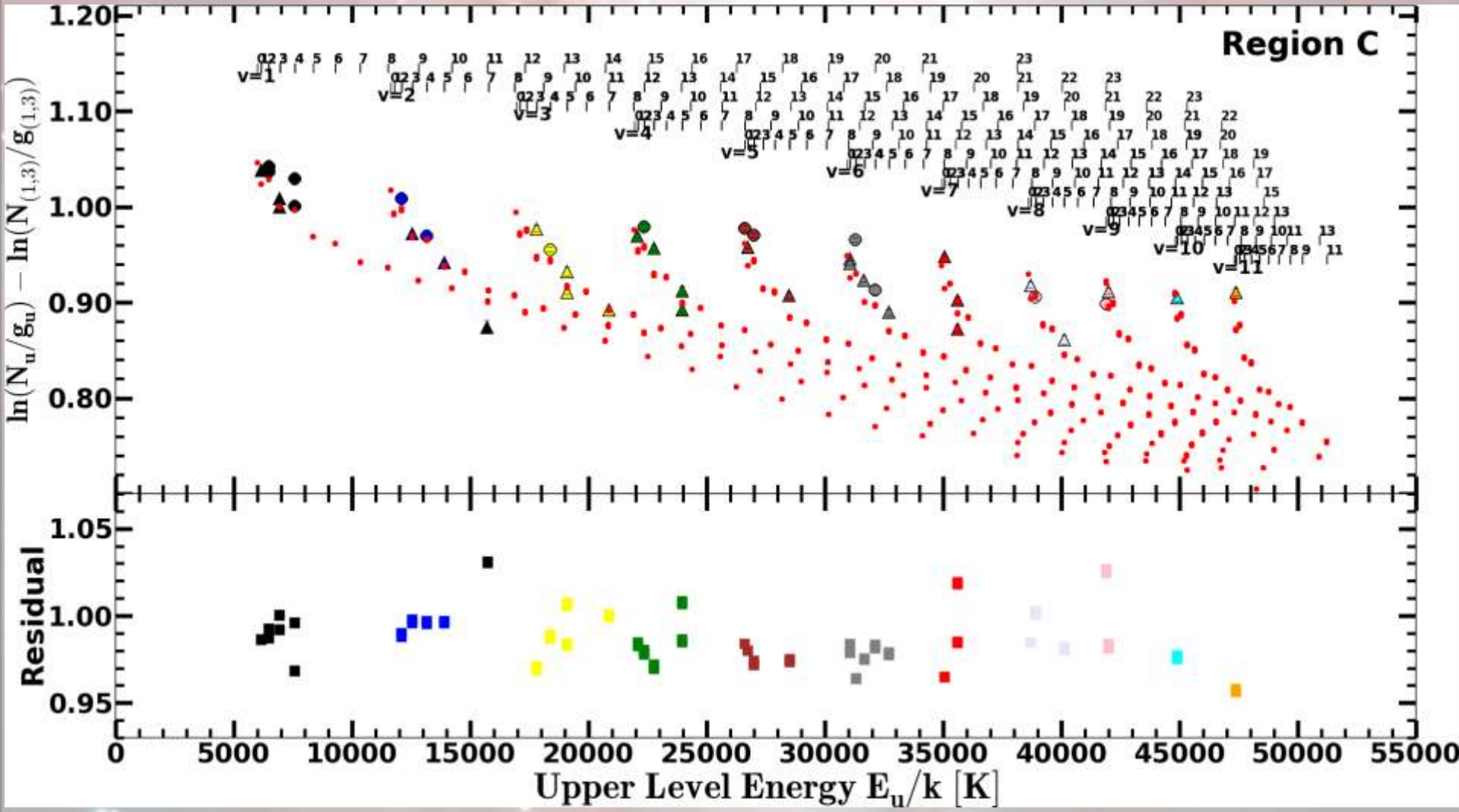
Comparison Data to PDR Model



Comparison Data to PDR Model



Comparison Data to PDR Model



Derived Densities

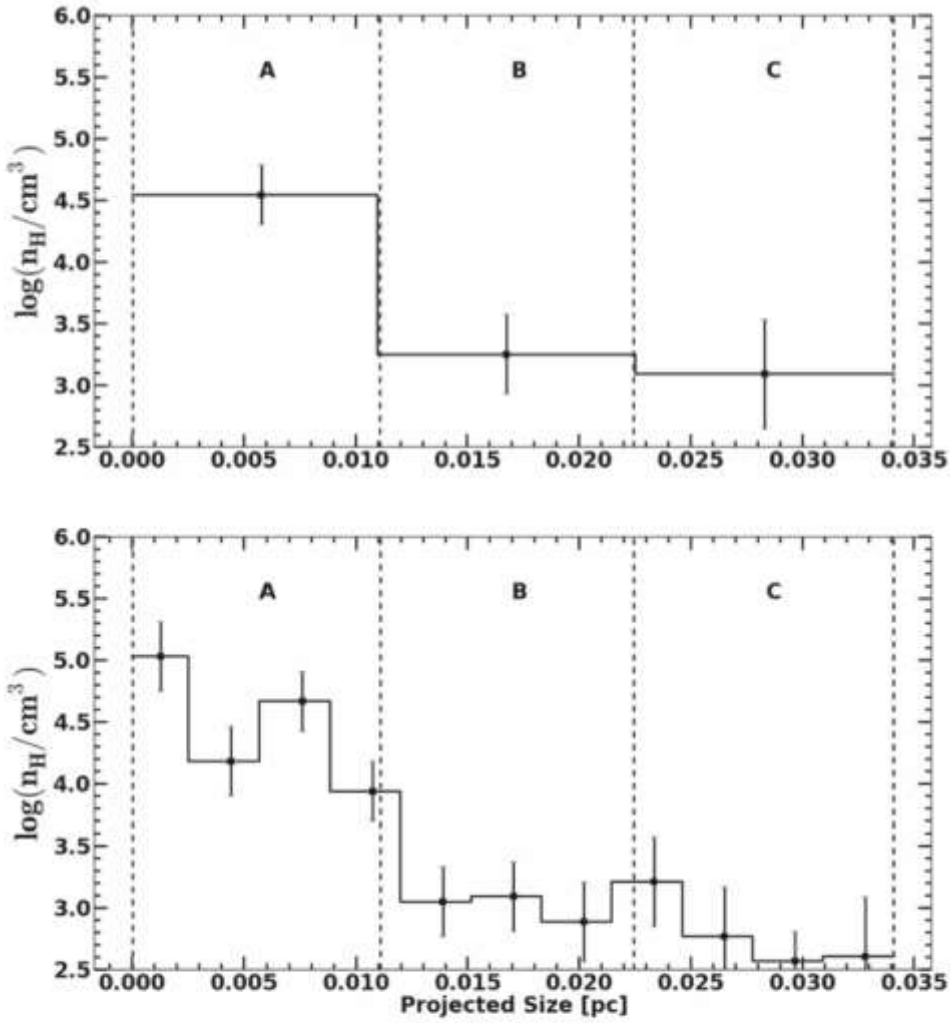


Figure 10. The top plot displays the estimated densities of regions A, B, and C (spatial resolution of ~5″ or 0.01 pc) from the PDR model of DB96. The solid line shows the estimate densities by DB96. The bottom plot presents the estimated densities of DB96 with a spatial resolution of ~1″ or 0.002 pc.

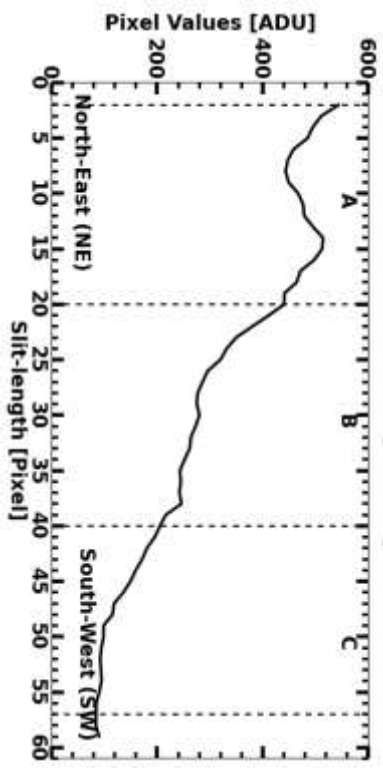
5″ = 0.01 pc

1″ = 0.002 pc

Summary and Conclusion

- We observed the NW filament of NGC 7023 in H- and K-bands using the high spectral resolution spectrograph, IGRINS.
- We detected 68 H_2 rovibration lines which are mostly UV excited.
  Dense regions show collisional de-excitation.
- We suggest that: The presence of the dynamic PDR front relative to the molecular cloud.
- We suggest that
  a high density ($n_H \approx 10^5$ cm^{-3}) clump with a size of ~ 0.002 pc embedded in lower density ($n_H \approx 10^3 - 10^4$ cm^{-3}) regions.

Line ratio (2-1 / 1-0)	OPR	V	ΔV_{FWHM}	n_H
0.41 ± 0.01	1.82 ± 0.11	3.64 ± 0.16	4.63 ± 0.34	10^5
0.48 ± 0.02	1.75 ± 0.09	3.46 ± 0.11	3.29 ± 0.26	10^3-10^4
0.56 ± 0.03	1.63 ± 0.12	3.39 ± 0.22	3.20 ± 0.27	10^3-10^4



2.5 ± 0.3 – position offset 10'' to the north from ours (Martini+1997)

Thank you!