A Direct Comparison of CO and H_2 from the Orion Molecular Shock

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High resolution long slit spectra of the Orion Peak 2 molecular shock simultaneously detect CO v=1-0 P(3) through P(6) and H_2 0-0 S(9) emission near 4.7 μm. Since the H_2 line has a significantly higher energy upper state yet is more wide spread than the CO emission, temperature alone is probably not the dominant constraint. More likely is that the CO traces higher densities. The CO lines are displaced further from the cloud rest velocity than the H_2 emission, suggesting the CO may arise in cooled post-shock gas. CO line ratios fail to specify a single temperature and density, but further study of this wavelength region should prove critical for understanding molecular shocks.

1. Introduction

Understanding molecular shocks represents a crucial piece of astrophysical knowledge. This is because shocks heat, accelerate, compress, and chemically process the gas and dust in the interstellar medium. We are now finding molecular shocks to be quite common; they are seen around star forming regions, planetary nebulae, Herbig-Haro objects, stellar outflows, and supernova remnants. Finally, the energy of molecular shocks makes the dominant constiuent of the dense ISM, H_2, directly observable from the ground.

Arguably, the two most important molecules in the ISM are H_2 and CO. It is possible to observe the H_2 v=0-0 S(9) line at 4.7 μm simultaneously with CO v=1-0 P branch lines, affording a direct comparison of the two molecules. The transition properties are such as to make the two molecules complementary tracers. H_2 0-0 S(9) has an upper state energy $E/k = 10261.3\ K$ and an Einstein A value of $A_{S9} = 4.9 \times\ 10^{-7}\,s^{-1}$. The corresponding values for CO 1-0 P(3) are $E/k = 3100.0\ K$ and $A_{P3} = 20.6\,s^{-1}$.

2. Observations & Results

We obtained spectra of shock-excited H_2 and CO from Orion Peak 2 in 1992 using CGS4 at UKIRT and in 1994 using CSHELL (Green et al. 1993) at the IRTF. The CGS4 observations employed 5″ pixels and gave $R \equiv \frac{\lambda}{\Delta\lambda} = 10,000$. We detected H_2 0-0 S(9) and CO 1-0 P(3) through P(6) [Fig. 1]. The CSHELL observations were have been binned in software to an effective resolution of 1.2 ″ per pixel. Based on lamp lines, the spectral resolution is $R = 14,000$. As seen in Figure 2, we detected the H_2 line and CO 1-0 P(3). Unfortunately, the relative positions of the CGS4 and CSHELL observations are unknown.

A quick inspection of Figure 1 shows two primary results. First, the CO emission peak is offset from the H_2 peak by ≈10″. This confirms similar behavior seen by Geballe & Garden (1990) in Orion Peak 1. Second, the individual CO lines are roughly 50% of the H_2 emission strength, demonstrating the potential importance of CO cooling. We note that absorption by CO in the surrounding cloud may affect the CO line profiles and would increase the importance of CO cooling (Walther et al. this volume).

From Figure 2, we see that the lines also appear kinematically distinct. The CO lines are redshifted 15-20 km s^{-1} more than the H_2 line. Furthermore, the H_2 line appears broader where the CO emission is weak. The FWHM of the H_2 line ranges from 30 to 45 km s^{-1} while the CO line has a fairly constant FWHM of 36 km s^{-1}.

3. CO Line Ratios

We can compare the observed CO line ratios with predicted populations in an effort to determine density and temperature of the emitting gas. Because the radiative decay times are short, we assume that each collision up to v=1 will lead directly to a photon. We use analytic expressions (McKee et al. 1982) for the population of the ground vibrational state as a function of density and temperature. These expressions are accurate to 50% for $n > 10^4\ cm^{-3}$, $T > 250\ K$ and CO–H_2 collisions (Viscuso & Chernoff 1988). A density of $n \gtrsim 10^{6.5}\ cm^{-3}$ reproduces line ratios from a Boltzmann population.

Our results from the three line ratios are presented in Figure 3. The shaded regions denote density–temperature combinations allowed by each line ratio. The labeled contours indicate the value of the line ratio. From the figure, it is apparent the P(6):P(5) and P(6):P(4) ratios are consistent with hot, dense gas. The P(6):P(3) ratio does not agree with other ratios; the 1-0 P(3) line is too strong by factor of 2.

4. DISCUSSION

The CO and H_2 emission clearly come from different gas. Since the H_2 line has a significantly higher energy upper state yet is more wide spread than the CO emission, temperature alone is probably not the dominant constraint. More likely is that the CO traces higher densities, such as from an inhomogeneous pre-shock medium or compression of the shocked gas as it cools. As post-shock gas cools and compresses, it also accelerates until reaching the shock velocity. The CO lines are displaced further from the cloud rest velocity than the H_2 emission, suggesting the CO may arise in cooled post-shock gas. Higher pre-shock densities may still be necessary to explain why the H_2 emission is narrow where CO is strong and broad where no CO is detected.

It is unfortunate the CO line ratios do not clearly define the emitting region's density and temperature. Optical depth and/or scattering are unlikely to resolve this issue. Improved analytic functions which include CO–H collisions may help, but the most dramatic advances will come observationally. Observations of higher P branch transitions, for example, would better constrain the range of acceptable parameters. Further study along the lines presented here should greatly advance our knowledge of molecular shocks.

This work made use of the CO linelist generously made available through anonymous ftp by D. Goorvitch.

REFERENCES

Geballe, T. R. & Garden, R. P. 1990, ApJ, 365, 602

Greene, T. P., Tokunaga, A. T., Toomey, D. W., & Carr, J. S. 1993, SPIE, 1946, 313

McKee, C. F., Storey, J. W. V., Watson, D. M., & Green, S. 1982, ApJ, 259, 647

Viscuso, P. J. & Chernoff, D. F. 1988, ApJ, 327, 364

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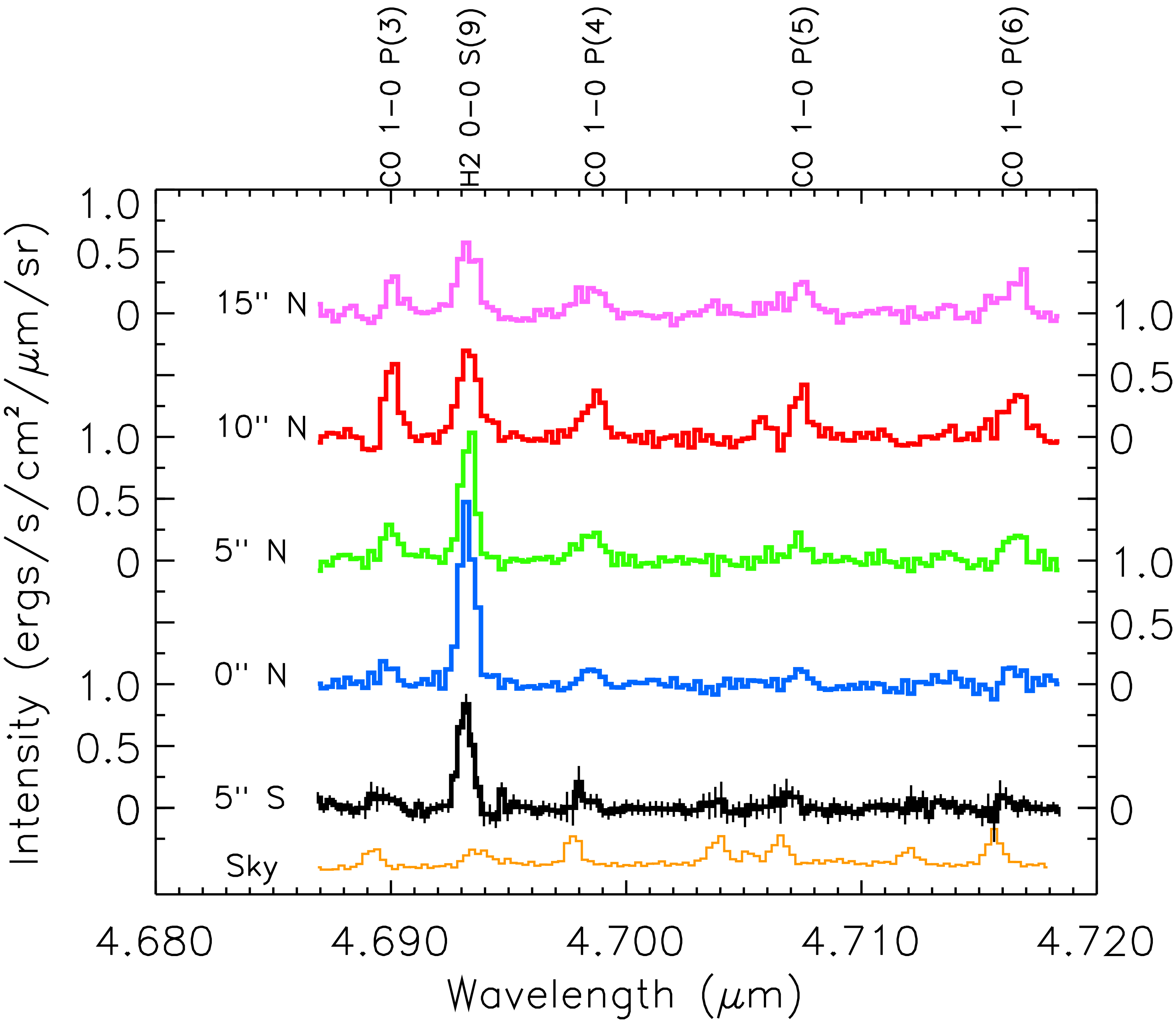
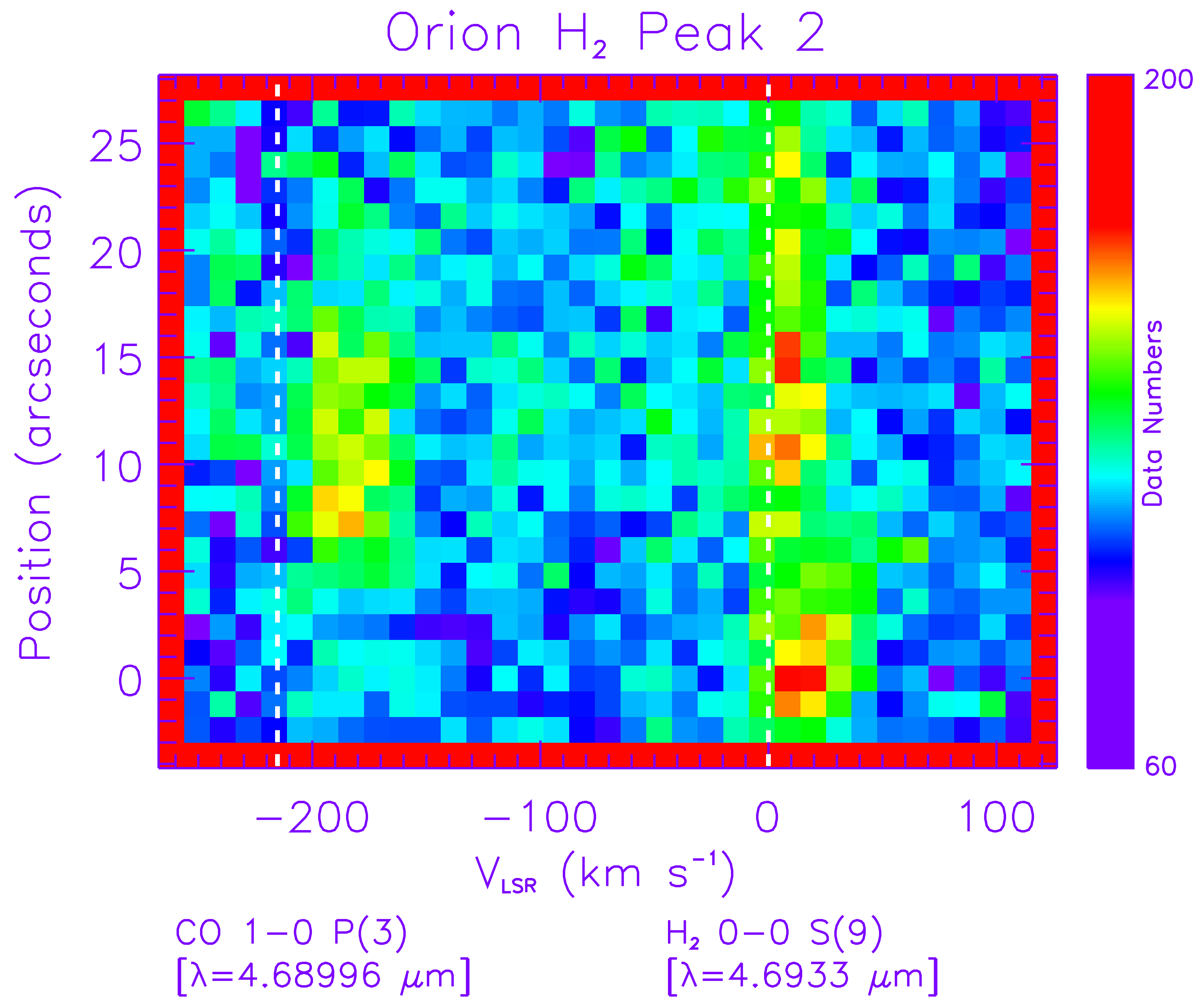
Fig. 1.— Long slit spectra of Orion H_2 Peak 2 taken with CGS4 at UKIRT. Each pixel covers 5″ spatially. The rows with significant emission are shown and labeled relative to the location of Peak 2. The spectral resolution is 30 $\mathrm{km\,s^{-1}}$. Each emission line is labeled. The CO lines are strongest about 10″ N of the H_2 peak. Errors, which are dominated by atmospheric absorption and cancellation, are shown on the 5″ S spectrum. The night sky spectrum at the bottom (without any intensity scale) shows the location of strong terrestrial lines (emission peaks).

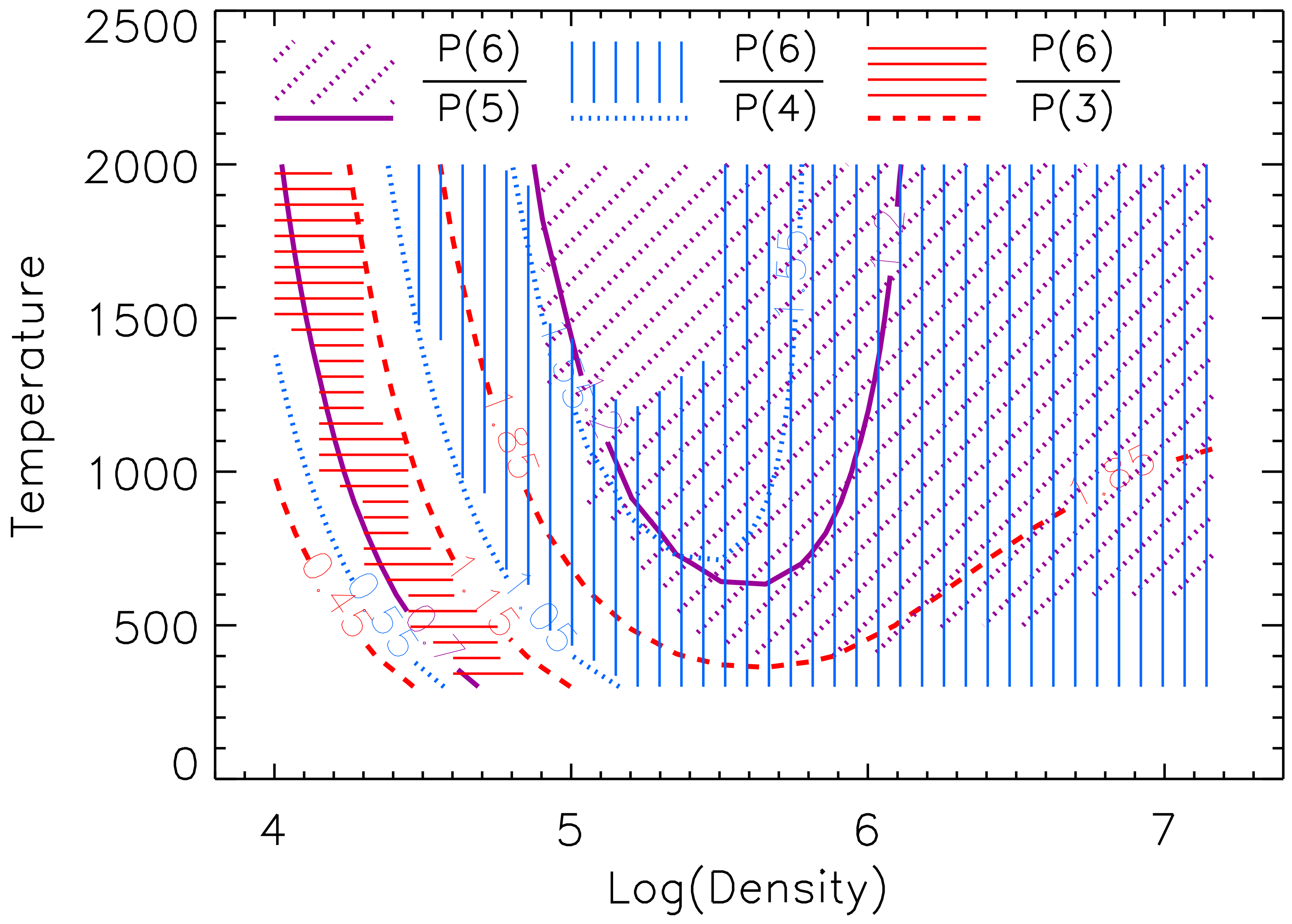
Fig. 2.— Long slit spectra taken with CSHELL at the IRTF. Pixels have been binned (1.2″ and 11 $\mathrm{km\,s^{-1}}$) to improve the signal-to-noise. The H_2 0-0 S(9) line shows considerable velocity structure: it is bright and wide where the CO 1-0 P(3) emission is weak (near 0″), is narrowest where the CO emission is strong (10″), and is broad again, but weaker, near 25″(weak CO emission). The CO emission has a fairly constant width. The CO line is shifted further from zero velocity (dashed white lines). The velocity scale is for H_2. If present, the ^{13}CO 1-0 R(9) line would have its zero velocity at -127 $\mathrm{km\,s^{-1}}$.

Fig. 3.— The $log(n) - T$ plane showing the parameter space permitted by CO line ratios. Labeled contours show the values of the different ratios, which all peak for $log(n) \approx 5.2$ and $T \gtrsim 1500\ K$. The shaded regions define the parameter space available for each line ratio. The 1-0 P(6):1-0 P(3) ratio does not overlap with the other two ratios; the 1-0 P(3) intensity would have to be reduced by a factor of 2 to reconcile this ratio with the others. Line ratios characteristic of Boltzmann distributions are obtained for $log(n) \gtrsim 6.5$.



CO 1–0 P(3)
H2 0–0 S(9)
CO 1–0 P(4)
CO 1–0 P(5)
CO 1–0 P(6)
15'' N
10'' N
5'' N
0'' N
5'' S
Sky
Intensity (ergs/s/cm²/μm/sr)
Wavelength (μm)
4.680
4.690
4.700
4.710
4.720
1.0
0.5
0


Orion H$_2$ Peak 2
Position (arcseconds)
25
20
15
10
5
0
−200
−100
0
100
V$_{LSR}$ (km s^{-1})
200
Data Numbers
60
CO 1−0 P(3)
[λ=4.68996 μm]
H$_2$ 0−0 S(9)
[λ=4.6933 μm]


P(6)/P(5)
P(6)/P(4)
P(6)/P(3)
Temperature
Log(Density)
2500
2000
1500
1000
500
0
4
5
6
7
0.45
0.55
1.05
1.85