Formation and Development of Molecular Clouds: Prospects for high resolution spectroscopy with CCAT

Implications of the Conference Presentations (not really a summary) With the Intent of Initiating Discussion

Paul Goldsmith

What do the themes of the papers presented at the conference suggest about what we want to do with CCAT relative to this topic?

- Many interesting complementary astronomical problems were discussed. It is probably not helpful to try and make a complete listing of these since you've all heard these as well as I. But this list would include
  - Galactic Nucleii
  - Starburst Galaxies
  - Distant Galaxies and Cosmic Infrared Background
- All of these deserve close attention and will undoubtedly be considered as requirements and instrumentation plan for CCAT are developed. Require spectroscopy, but not with R lower than 10^5, and not large-area mapping

Challenging problems require specialized instrumentation

- Probing LOS magnetic field through Zeeman effect requires **measurement of the circular polarization of spectral lines**
  - Array receivers would be helpful, but not certain what areas need to be covered
  - Additional requirement for heterodyne system
- Probing Plane-of Sky B-field through dust grain polarization requires **measurement of linear polarization of continuum radiation**
  - Incoherent detector arrays are likely to be desired since signals are weak and many samples are required to obtain good field morphology and to exploit statistical techniques (e.g. Chandrasekhar-Fermi and extensions thereof)
  - Additional requirement for continuum camera system

How Do We Learn How Molecular Clouds Form and Evolve?

- Surveys of all different types provide basic data using different tracers
- Molecular clouds have structure over a very wide range of scales. Thus, "high resolution" surveys and studies of selected nearby clouds add critical information
- The combination of large-area and high resolution allows Increased spatial dynamic range, which in turn enables detection of new and perhaps critical morphology (e.g. filaments)
- Theoretical modeling has made major progress, and suggests that multiple forces are at work. Galactic-scale modeling also progressing – indicates that stellar feedback is required
- Models must strive to reproduce observed cloud structure at all scales
- Astrochemical observations are not unrelated to questions of cloud evolution and star formation but we are still learning how to use this caoability

Is Spectroscopy Necessary?

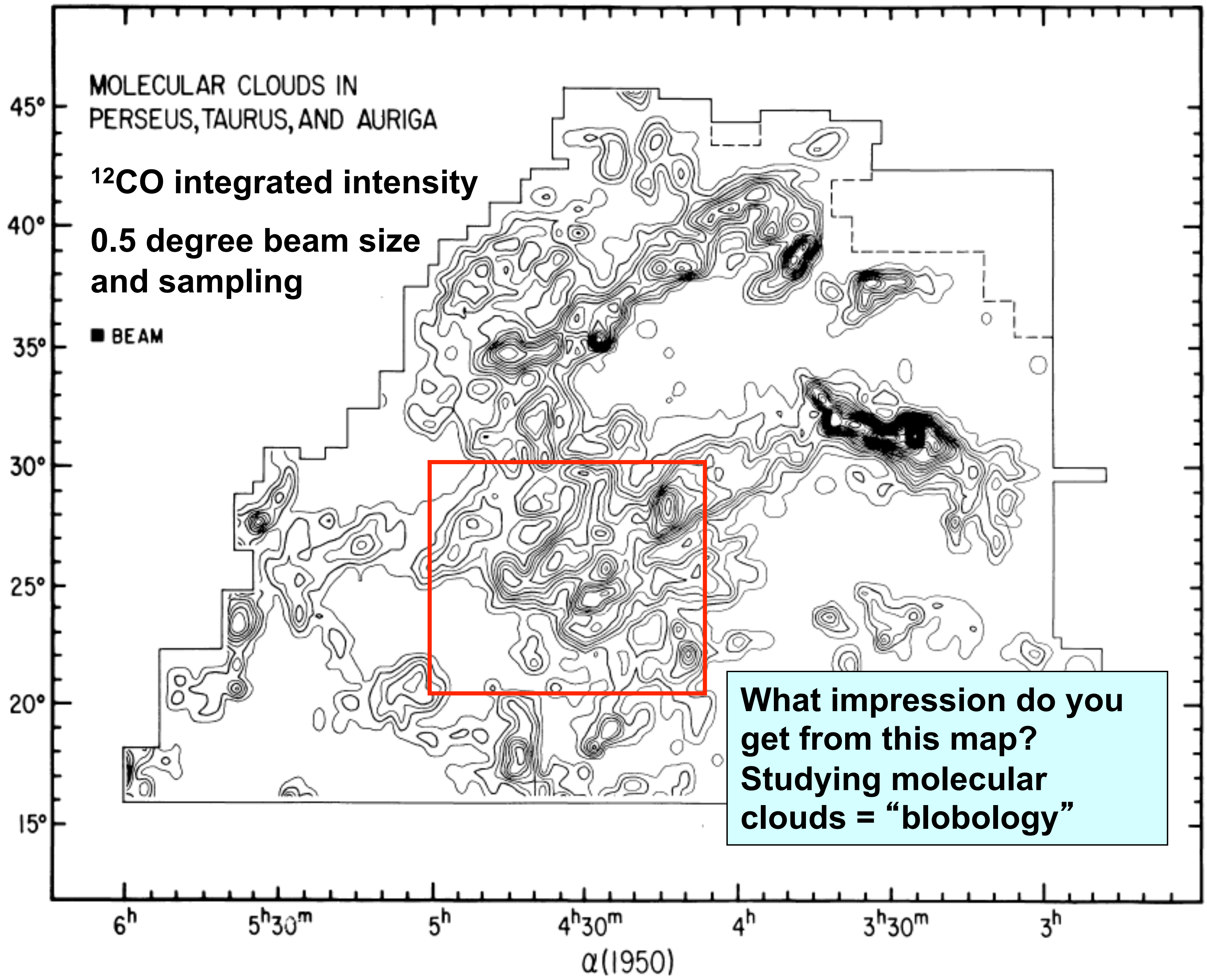
- The complexity of astrochemistry may suggest that we only use relatively invariant tracer, most plausibly dust continuum emission
- However, we may invert that argument to exploit astrochemical selectivity that enhances abundance of certain species in particular environments. Examples might include deuteration in cores, shock tracers, CI as probe of "dark molecular gas"…
- Answering some of the most critical questions demands spectral lines to trace kinematics. Some of the examples brought up in papers at this conference include
  - Cloud virial balance
  - Formation of filaments
  - Accretion of material onto filaments
  - Flows of material within filaments including fragmentation into cores
  - Transition from turbulence to coherence in cloud cores
- All of these occur on scales that are readily probed by CCAT rather than ALMA, as they are typically extended over quite large areas

Probing the Evolution and Structure of Molecular Clouds will Require Large-area High-spectral Resolution Imaging

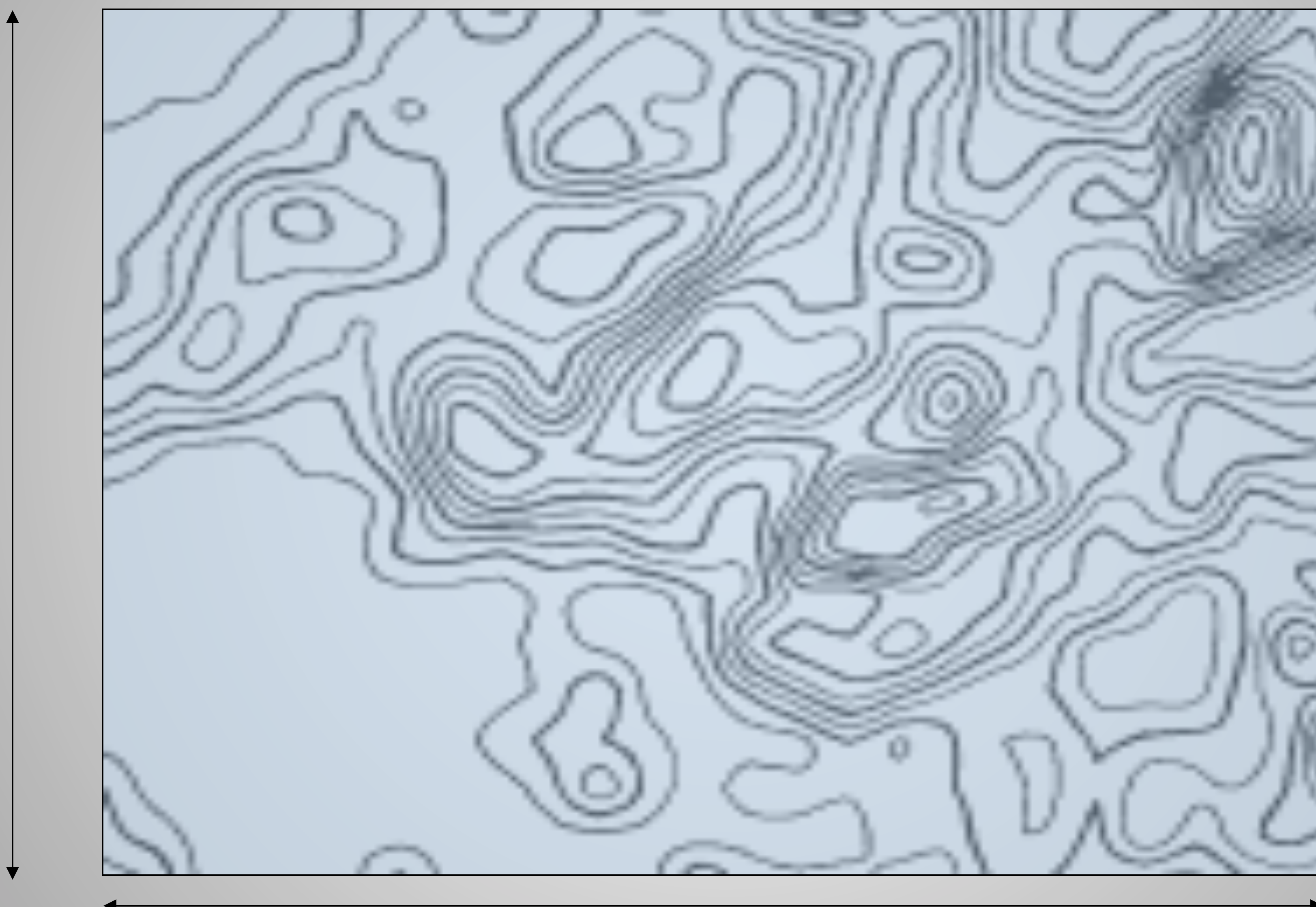
- Surveys will be important (general but not total agreement on this point)
- What tracers will add the most value?

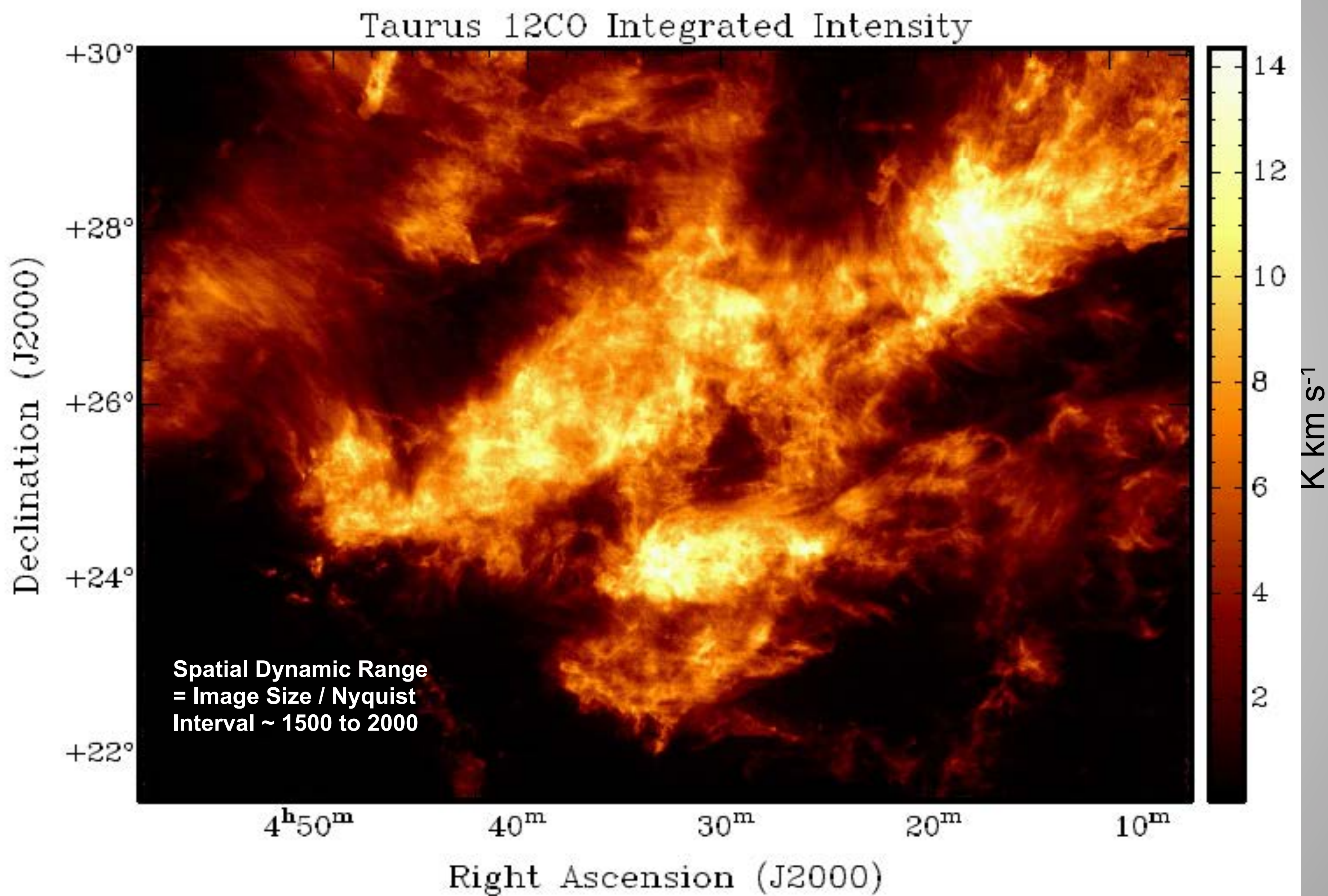
CCAT is allowing entry into a **new portion of discovery space** defined in terms of sensitivity X area coverage X frequency coverage X angular resolution X spectral resolution

We should be careful not to eliminate prematurely potentially valuable tracers. We need to combine results from simulations of the complex physics and chemistry with the information provided by various available data (ground based, Herschel, SOFIA …)



MOLECULAR CLOUDS IN
PERSEUS, TAURUS, AND AURIGA
^{12}CO integrated intensity
0.5 degree beam size
and sampling
BEAM
45°
40°
35°
30°
25°
20°
15°
6h
5h30m
5h
4h30m
4h
3h30m
3h
α(1950)
What impression do you get from this map? Studying molecular clouds = "blobology"


8.25 degrees
12 degrees



Taurus 12CO Integrated Intensity
+30°
+28°
+26°
+24°
+22°
Declination (J2000)
4h50m
40m
30m
20m
10m
Right Ascension (J2000)
14
12
10
8
6
4
2
K km s-1
Spatial Dynamic Range
= Image Size / Nyquist
Interval ~ 1500 to 2000

Potential Tracers for Use by CCAT

- We heard many interesting results and suggestions, but what can we take away?

- Medium-J CO lines, e.g. J = 4-3, J = 6-5, J = 7-6
  - Lower lines possible, but probably not adding too much relative to IRAM, SMT, LMT
  - Some higher lines and isotopologues can be done (limited by atmosphere)
- Both CI fine structure lines (492 and 809 GHz)
- Selected probes – hydrides, deuterated hydrides, molecular ions

WHAT MAPPING CAN BE DONE?

Time Requirement for Large-scale Survey Carried Out With On-the-Fly (OTF) Mapping

Assume we have a heterodyne array

T_s = average system temperature (SSB including atmosphere)

δf = channel width $\delta f(\mathrm{MHz}) = \delta v(\mathrm{km/s})/\lambda(\mathrm{mm})$

ΔT = rms per beam in reconstructed survey map (antenna temp.)

N_{pix} = # of pixels in the array

t_{int} = integration time per pointing of array

t_{surv} = time to carry out the survey

ε = OTF mapping efficiency (includes time for calibration, acceleration, slewing, reference position observations)

Ω_{surv} = solid angle of the survey

Ω_b = solid angle of the antenna beam = $1.13\theta_{fwhm}^2$

For single pointing we have usual radiometer equation

$\Delta T = T_{sys}/[\delta f\ t_{int}]^{0.5}$

Assume we carry out a large ($\Omega_{surv} >> \Omega_b$) survey with proper (Nyquist) sampling, but reconstruct the final image to angular resolution equal to Θ_{fwhm}

$$\Omega_{surv}/\Omega_b = N_{pix}\ t_{surv}\ \delta f\ (\Delta T/T_{sys})^2\ \varepsilon$$

It does not matter how your array pixels are distributed as long as you use them all in collecting the data

$$t_{surv} = (\Omega_{surv}/\Omega_b)(T_{sys}/\Delta T)^2/(\varepsilon\ \delta f\ N_{pix})$$

Some reasonable values for CCAT to image a **Galactic** source

$T_{sys} = 500$ K

$\delta f = 1$ MHz

$\varepsilon = 0.5$

$\Delta T = 0.1$ K (certainly arbitrary but plausible)

$$t_{surv} = (50/N_{pix})(\Omega_{surv}/\Omega_b)$$

(Galactic) $t_{surv} = (50/N_{pix})\ \Omega_{surv}/\Omega_b$

As an example, choose f = 809 GHz, λ = 0.371mm

Θ_{fwhm} = 3.67" = 0.061'

$\Omega_b = 0.0042'^2$

For $\Omega_{surv} = 1^{o2} = 3600'^2$, $\Omega_{surv}/\Omega_b = 8.6 \times 10^5$

$N_{pix}\ t_{surv} = 4.32 \times 10^7$ s

Time vs. Pixel Number for 1^{o2} Galactic Survey	
N_{pix}	T_{surv} (s)
1	4.32×10^7
32	1.4×10^6
128	3.4×10^5 (94 hr)
512	8.5×10^4 (24 hr)

Nearby Galaxies are Important Targets of CCAT with Heterodyne Array: Example - NGC 6946 (D = 3 Mpc)

(A difficult challenge because you cannot observe it from Chile)

140 CCAT beams at 690 GHz

$t_{surv} = (\Omega_{surv}/\Omega_b)(T_{sys}/\Delta T)^2/(\varepsilon\ \delta f\ N_{pix})$

4.3 km/s ⇔ 10 MHz

Ts = 500 K

$\Delta T = 0.01$ K

$\Omega_{surv} = 100'^2$

$\Delta\Theta = 4.3'' = 0.072'$ $\Omega_b = 5.8\mathrm{x}10^{-3}\ '^2$

$t_{surv} = 500\ (\Omega_{surv}/\Omega_b) = 8.5\mathrm{x}10^6/N_{pix}$

Time vs. Pixel Number for Extragalactic Image	
N_{pix}	T_{surv} (s)
1	$8.5\mathrm{x}10^6$
32	$2.7\mathrm{x}10^5$
128	$6.6\mathrm{x}10^4$ (18 hr)
512	$1.7\mathrm{x}10^4$ (4.6 hr)

Heterodyne Survey Synopsis

A 128 pixel 500 K heterodyne array with state-of-the-art performance would allow

1 sq.degree Galactic source image in 94 hr

50 sq. degree Galactic plane survey in 4700 hr

1 sq. degree extragalactic image in 18 hr

Survey of 50 nearby galaxies in 900 hr

Pick your tracer and source and go for it!

Personal Thoughts on Heterodyne Arrays for CCAT to Provoke Discussion

- Exploit one (or both) of three "good" CCAT bands initially to have maximum impact and address key science questions
  - 400 – 500 GHz (CO J = 4-3 [461], CI $^3P_1$-$^3P_0$ [492])
  - 600 – 700 GHz (CO J = 6-5 [692], isotopologues)
  - 800 – 950 GHz (CO J = 7-6 [807], CI $^3P_2$-$^3P_1$ [809])
- "Dual color" is tricky due to different line strengths and atmosphere, but is more plausible with OTF mapping as sky is covered for all frequencies. Having two arrays in one dewar gains capability but complicates receiver design and increases cost
- Multiple frontend units are possible – occupy different portions of CCAT focal plane (but there will be competition for real estate. Simultaneous use is possible but a stretch
- Employ modular approach for frontends to allow for easy receiver changes as well as future upgrades

Personal Ideas on CCAT Heterodyne Receivers to Provoke Discussion

- Balanced mixers are highly advantageous due to easier LO distribution/injection as well as LO noise cancellation
- LO production and distribution with balanced mixers is entirely straightforward
- Sideband separating mixer would be even better – the atmospheric noise contribution is significant and would be reduced
- Avoid use of optics and quasioptics
- NO image derotation please – image rotation is an advantage!
- Digital FFT spectrometers should enable 10 GHz bandwidth per pixel by CCAT first light (limited by AD converters)
    - Direct digitization of first IF is attractive, but beware of feedback effects. This is worsened if it is all in single dewar => careful system design and testing needed

Additional Information

The following slides were added after the discussion. They give information about the frequencies of carbon monoxide transitions of key importance for CCAT and of the two CI transitions.

The atmospheric transition in the frequency ranges of interest are riddled with atmospheric absorption features. Observations will require careful calibration in order not to be confused by the telluric features. One useful strategy will be to ensure that the difference in elevation between signal and reference positions is minimized. It may be possible to use stronger telluric features in the passband to correct the atmospheric effects.

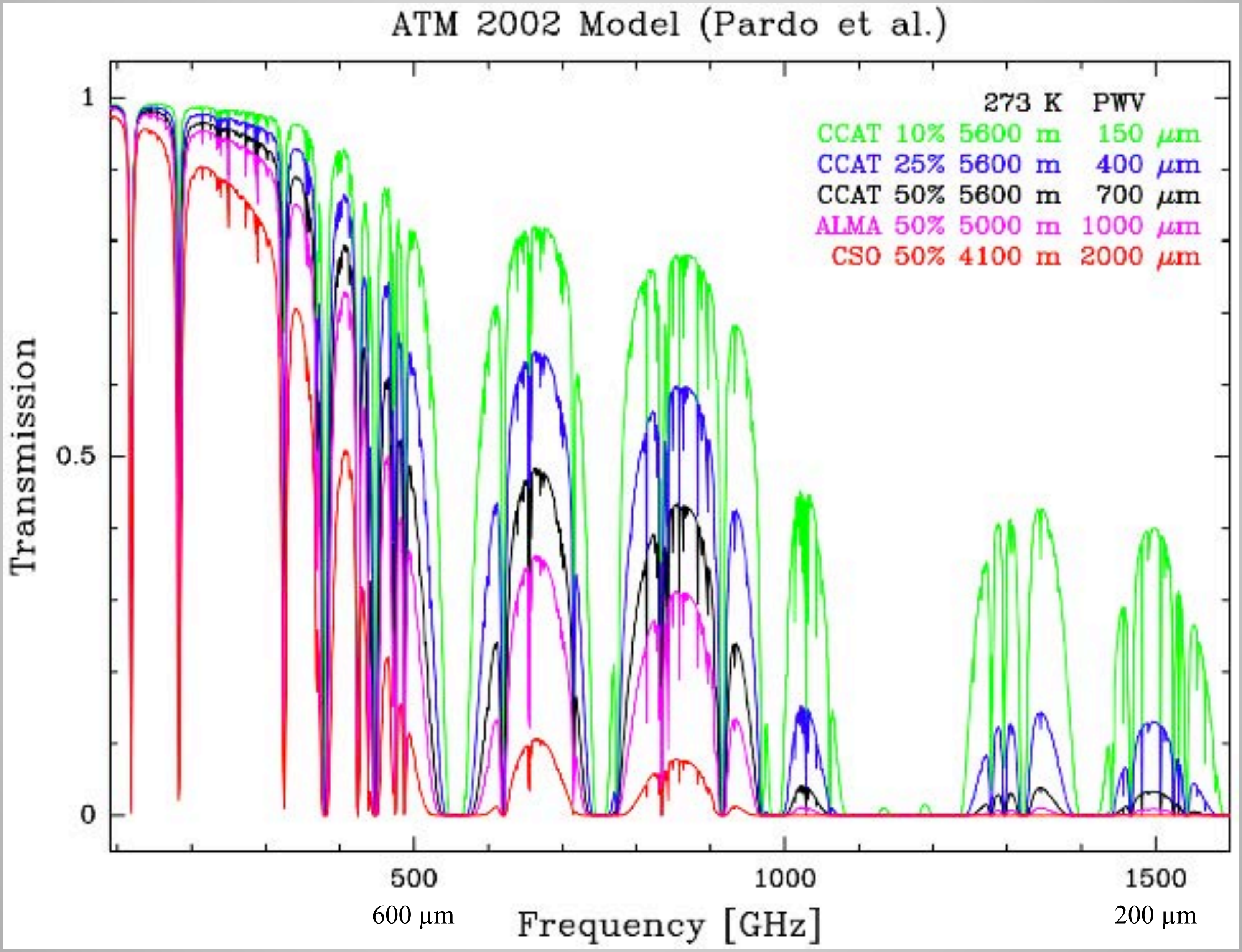
I did not mention the 13CI line issue, but it can be observed in the higher frequency line, and could be very valuable for resolving optical depth issues. For information on CI frequencies and about the hyperfine structure, see Klein et al. 1998, ApJ, 494, L125.

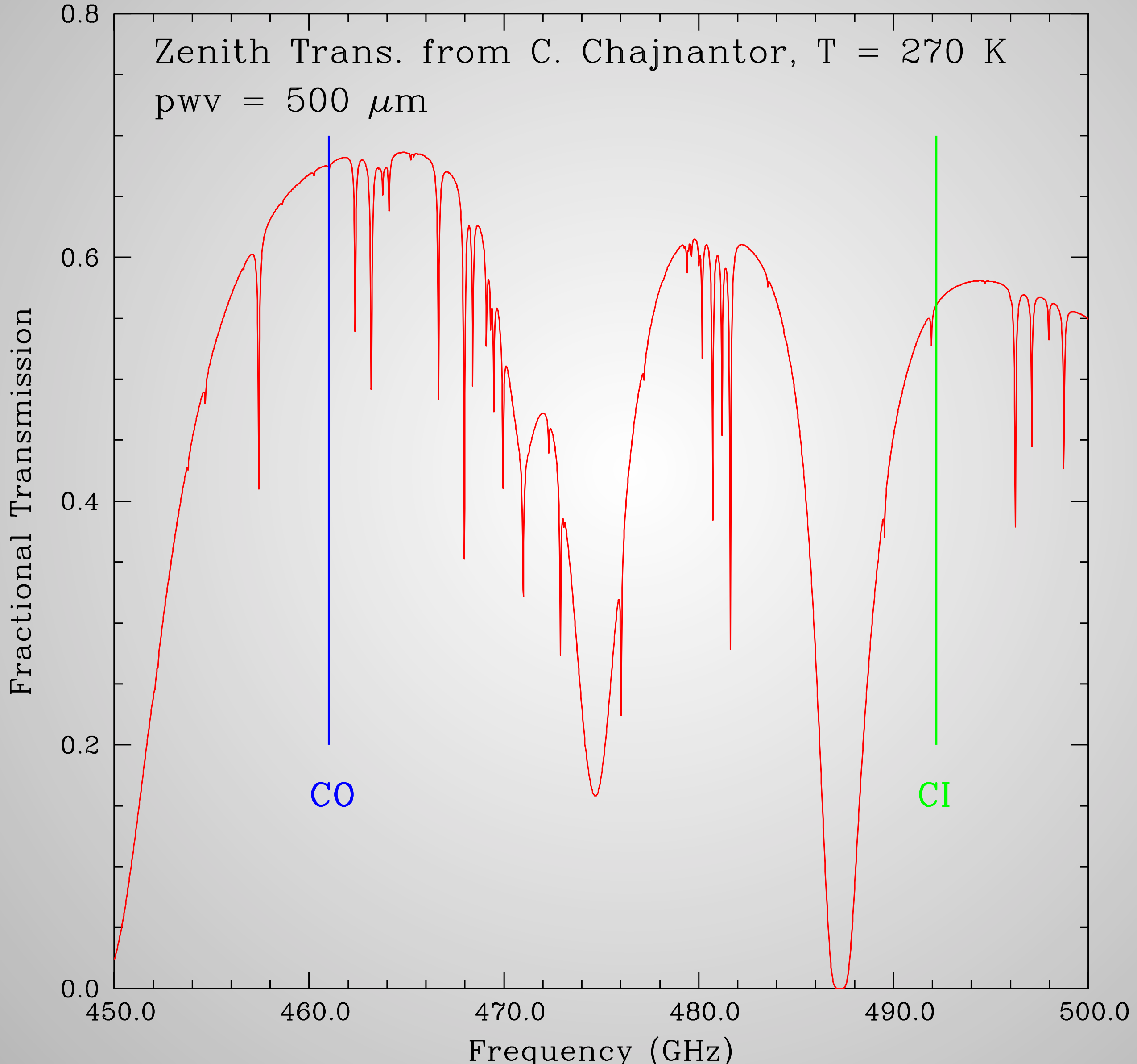
Candidate Spectral Lines of CO and [CI] for CCAT

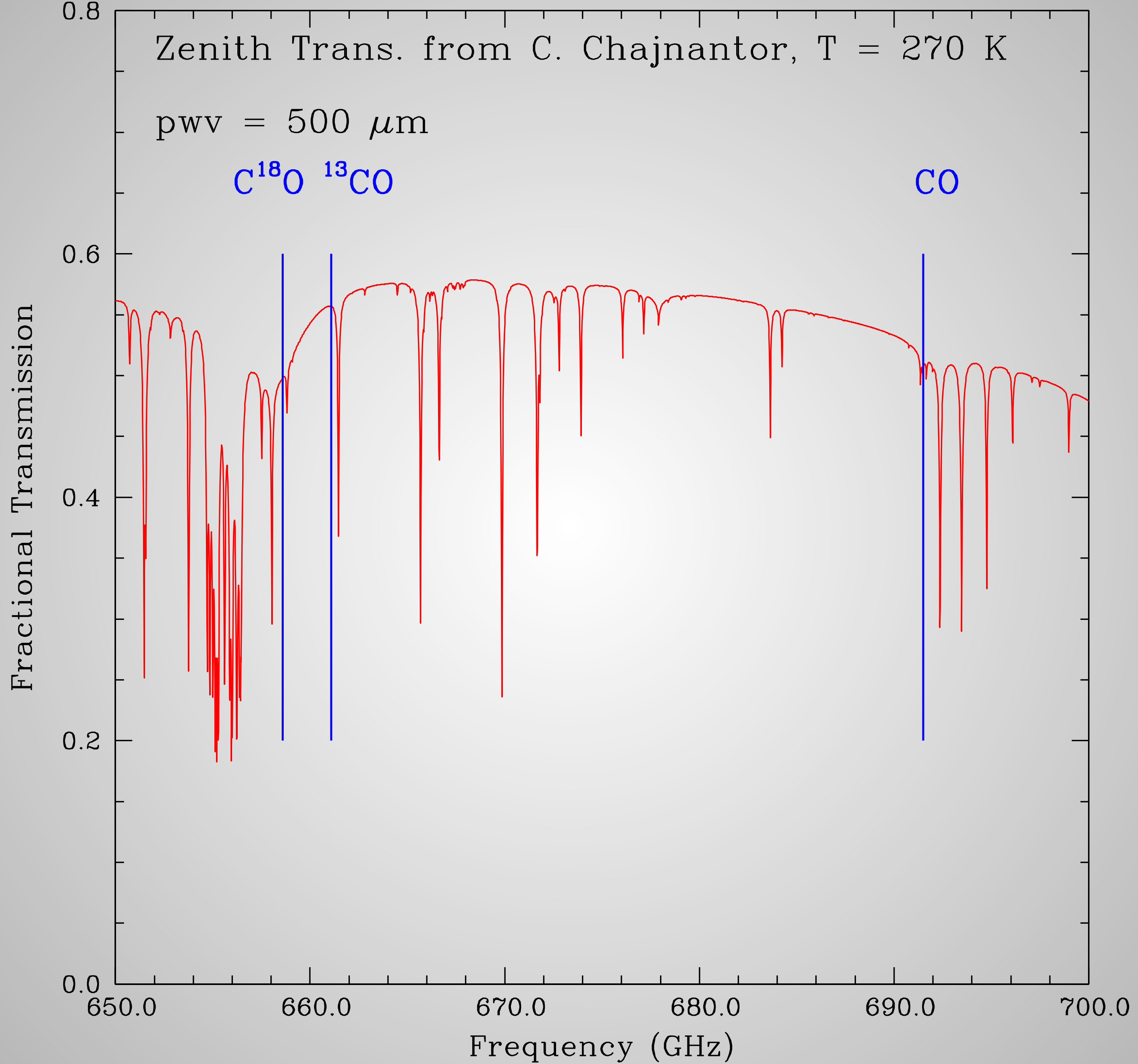
Frequencies of Transitions of CO and Isotopologues for CCAT at ≤ 1 THz (GHz)			
Transition	**CO**	**^{13}CO**	**$C^{18}O$**
4 – 3	461.0	440.8	439.1
5 – 4	576.3	550.9	548.8
6 – 5	691.5	666.1	658.6
7 – 6	806.7	771.2	766.3
8 – 7	921.8	881.3	877.9
9 – 8	1036.9	991.3	987.6

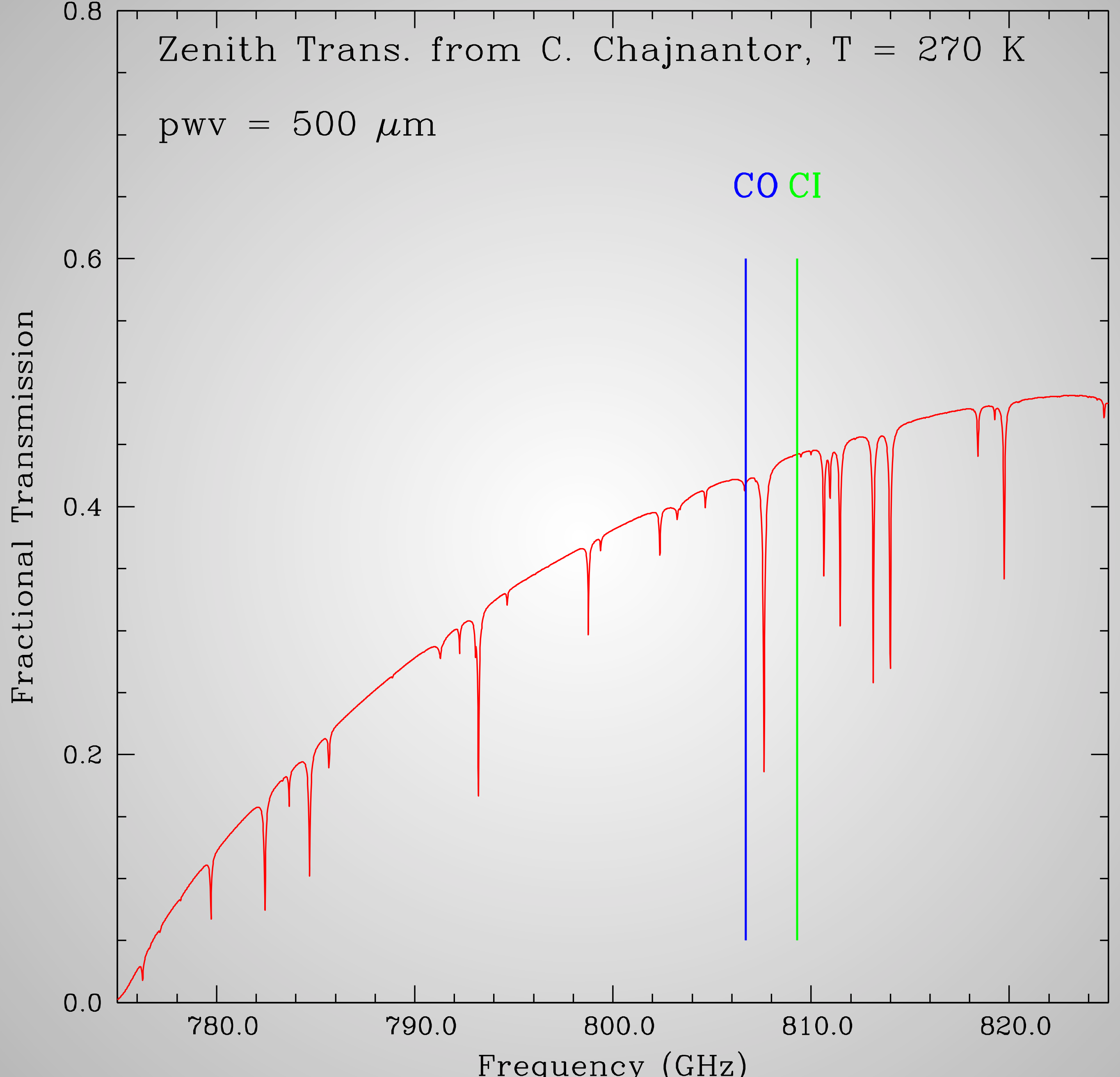
Frequencies of [CI] Transitions (GHz) (Fractional Strength)				
Transition	**[CI]**	**[^{13}CI] F=3/2–1/2**	**[^{13}CI] F=5/2 –3/2**	**[^{13}CI] F=3/2 – 3/2**
$^3P_1 - {}^3P_0$	492.162 3/2-1/2 and 1/2-1/2 separated by only ~4 MHz Klein+ 1998			
$^3P_2 - {}^3P_1$	809.342	809.126 (0.333)	809.494 (0.600)	809.121 (0,067)

Atmospheric Transmission (model)




Zenith Trans. from C. Chajnantor, T = 270 K
pwv = 500 μm
CO
CI
0.0
0.2
0.4
0.6
0.8
450.0
460.0
470.0
480.0
490.0
500.0
Fractional Transmission
Frequency (GHz)


Zenith Trans. from C. Chajnantor, T = 270 K
pwv = 500 μm
C18O
13CO
CO
Fractional Transmission
Frequency (GHz)
0.0
0.2
0.4
0.6
0.8
650.0
660.0
670.0
680.0
690.0
700.0


Zenith Trans. from C. Chajnantor, T = 270 K
pwv = 500 μm
CO
CI
0.8
0.6
0.4
0.2
0.0
Fractional Transmission
780.0
790.0
800.0
810.0
820.0
Frequency (GHz)