Large-Scale Structure of the Molecular Gas in Taurus Revealed by High Spatial Dynamic Range Spectral Line Mapping

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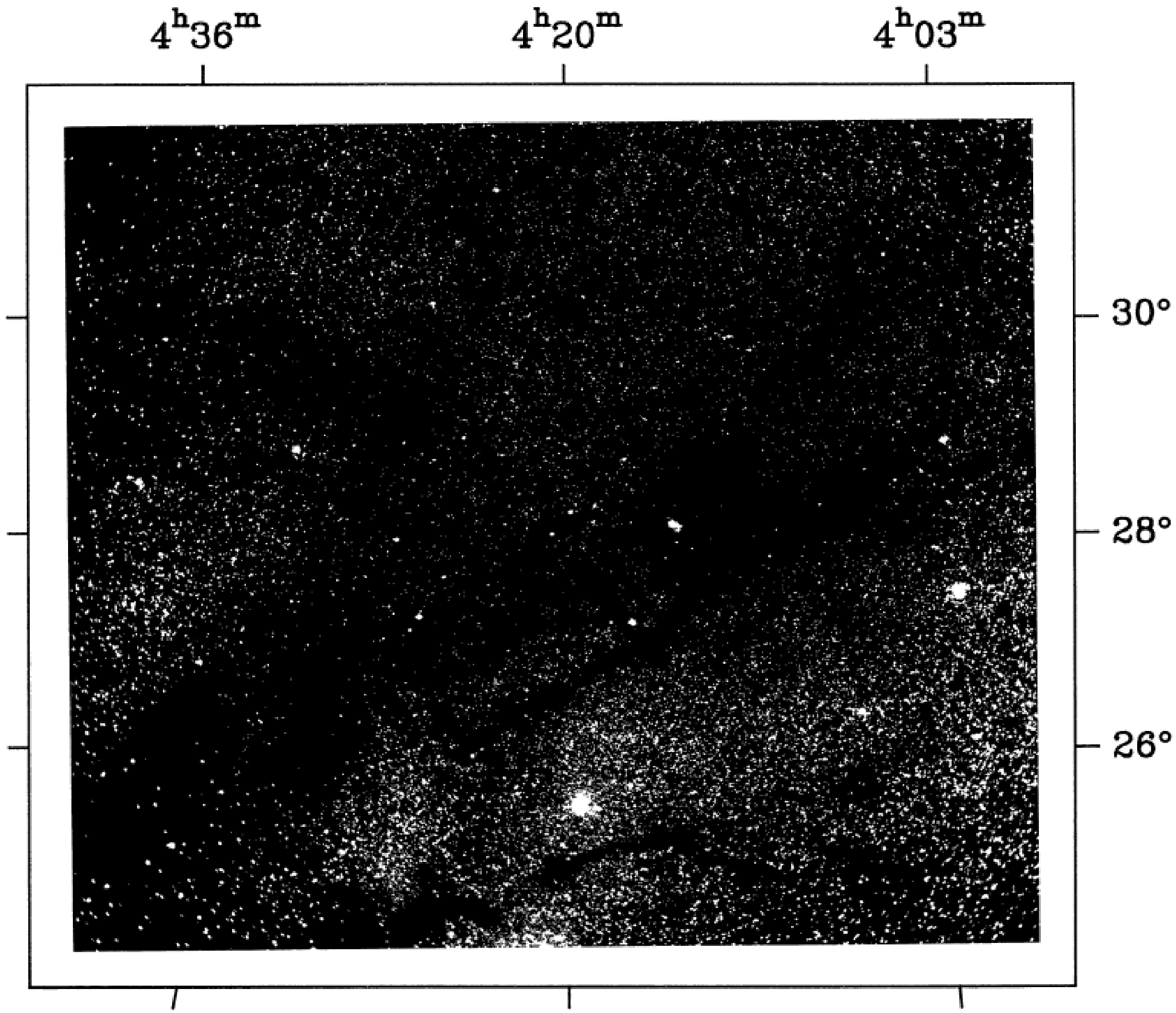
OPTICAL IMAGE OF TAURUS

It has Long Been Recognized as a Nearby Region Containing a Lot of Dust



Duvert, Cernicharo, & Baudry (1986);

from Barnard (1927)

Dust Extinction in IR Has Provided a New Tool for Probing Cloud Morphology

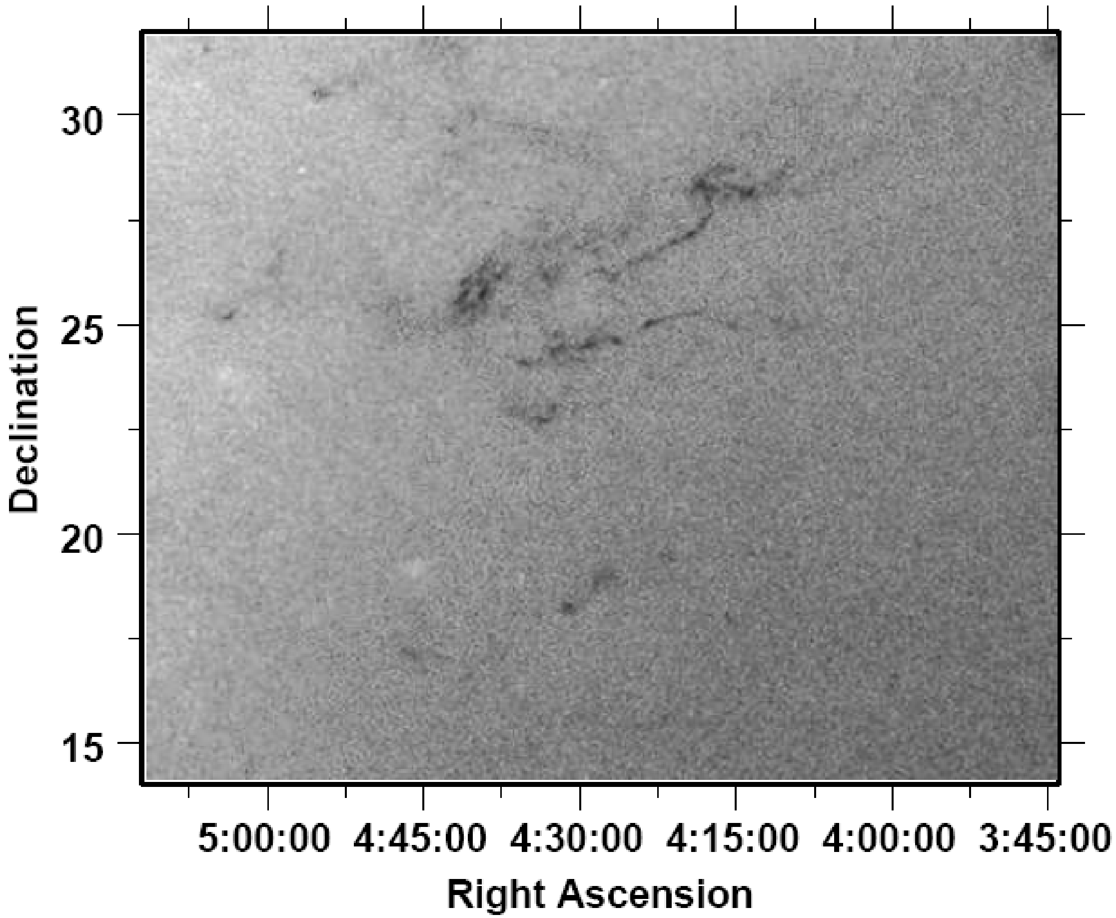


Figure 1. Star count map of the Taurus-Auriga dark clouds. This map was prepared for this paper from stars with J ≤ 16.5 in the 2MASS point source catalog downloaded from the IRSA archive. The intensity scale is proportional to the number of stars per square arcmin. The dark clouds are clearly visible as low density regions. Two small bright regions are the open clusters NGC 1647 (RA = 4^h46^m, Dec = 19°) and NGC 1750/1758 (RA = 5^h04^m, Dec = 24°).

Kenyon, Gómez, & Whitney (2007)

Observations of the Gas can Contribute Critical Information on

- **Gas Temperature**
- **Gas Column Density & Distribution**
- **Mass**
- **Kinematics**

1. Requires High Angular Resolution to Reveal Structure
2. Requires Extended Coverage to Trace Connection to Large Scale Structure
3. Focal Plane Array on MM Telescope is the Enabling Technology

The Taurus Molecular Cloud Complex: The Big Picture

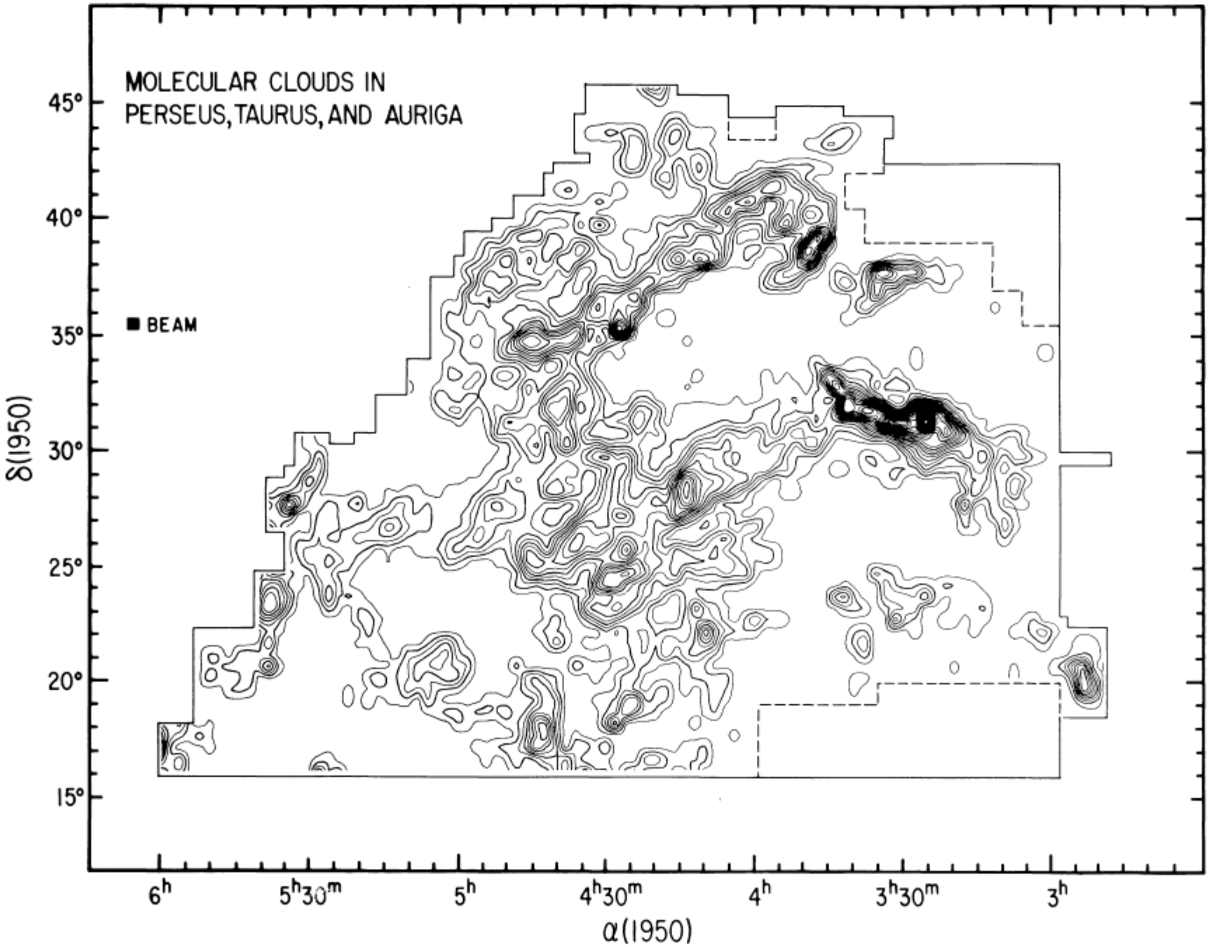
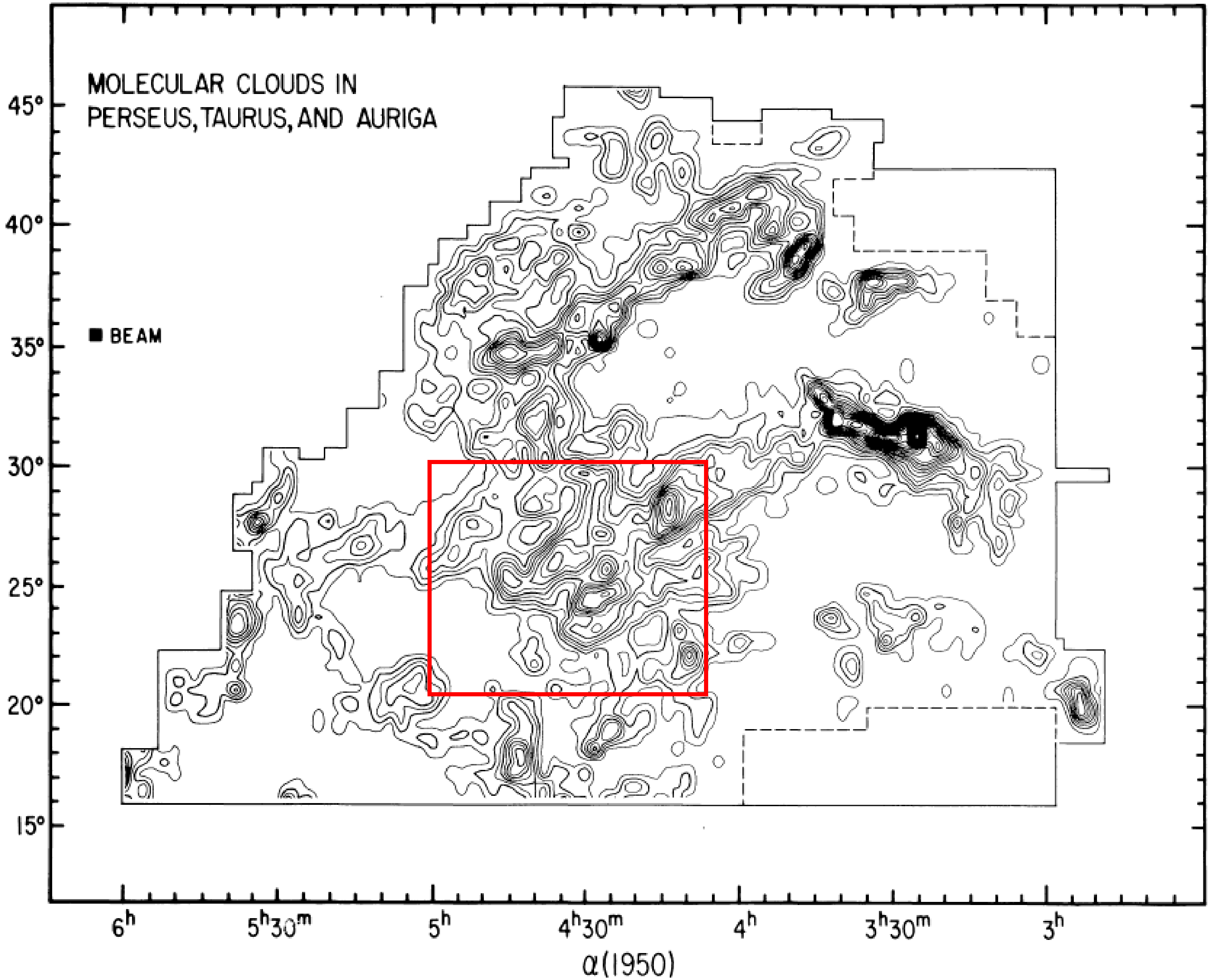


FIG. 1.—Velocity-integrated intensity of CO emission, W_{CO}. The lowest contour is 0.5 K km s^{-1}, and the separation between contours is 1.5 K km s^{-1}. The border of the surveyed region is indicated by the outer, solid line; in the small regions beyond the dashed line the map is undersampled, with a spacing of $4^m \times 1°$.

Ungerechts & Thaddeus 1987 ApJS

Distance = 140 pc

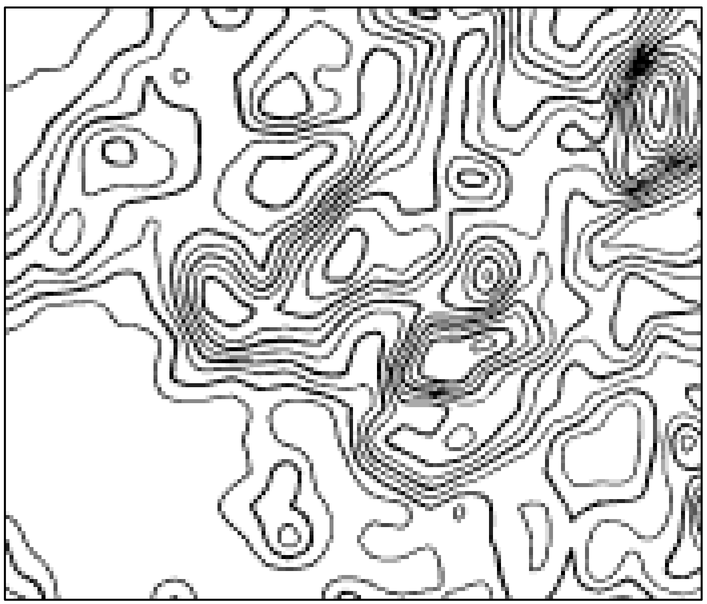
1 deg = 2.4 pc


MOLECULAR CLOUDS IN
PERSEUS, TAURUS, AND AURIGA
BEAM
45°
40°
35°
30°
25°
20°
15°
6h
5h30m
5h
4h30m
4h
3h30m
3h
α(1950)

~100 Square Degree Area of Taurus

elected from Ungerechts & Thaddeus (1987)

8.25 degrees



12 degrees

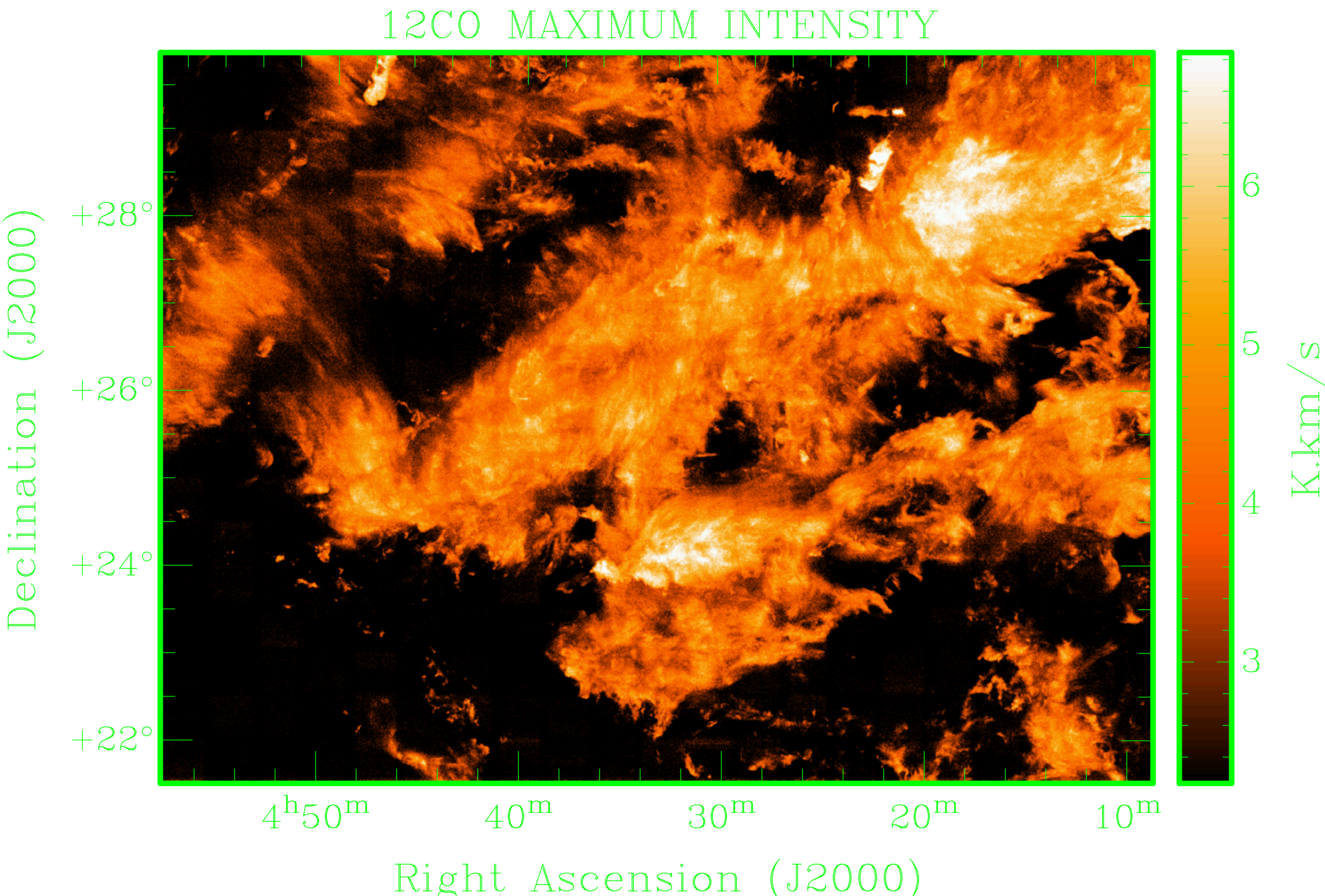
^{12}CO Integrated Intensity

0.5 Deg Beam Size and Sampling

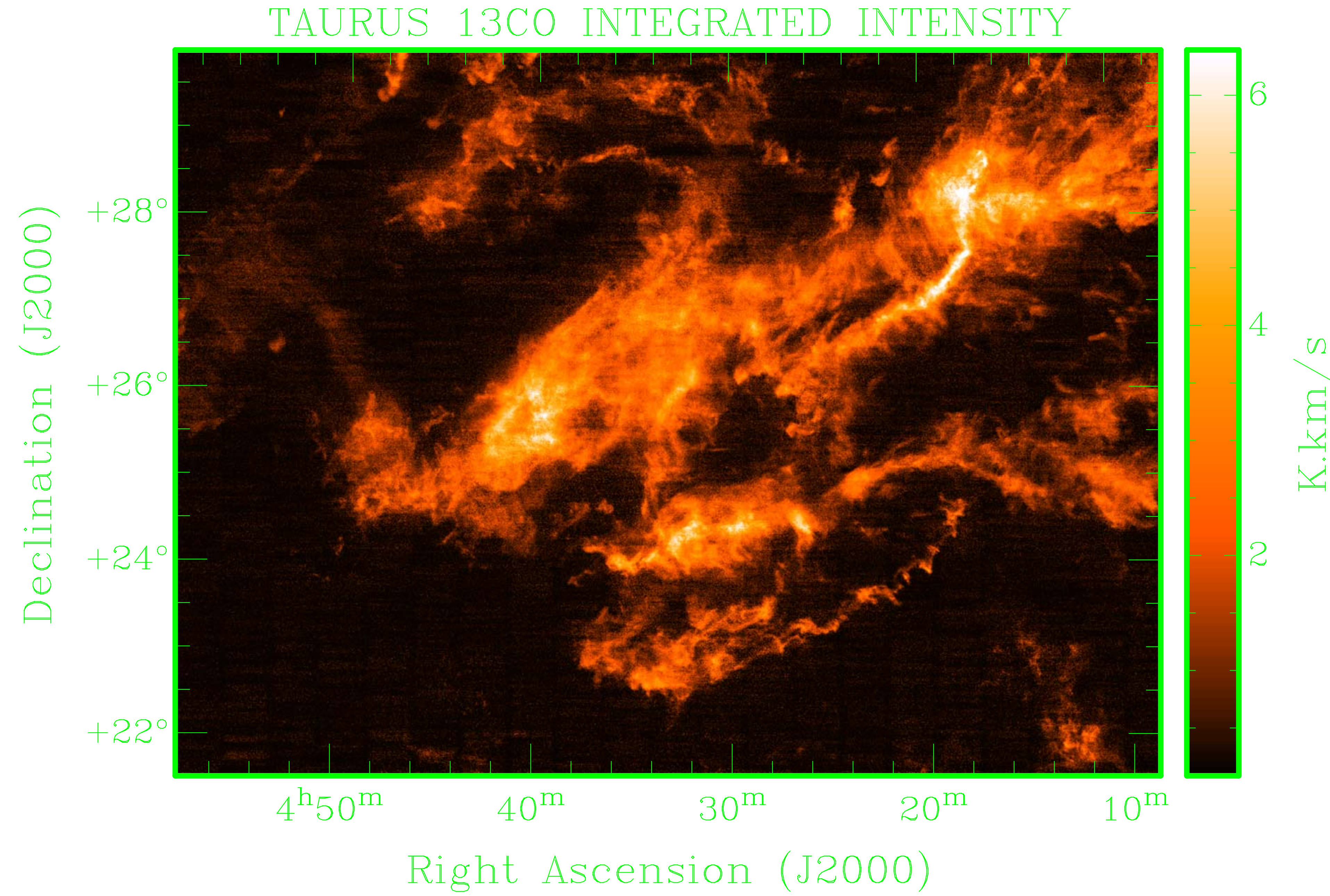
What impression do you get from this map?

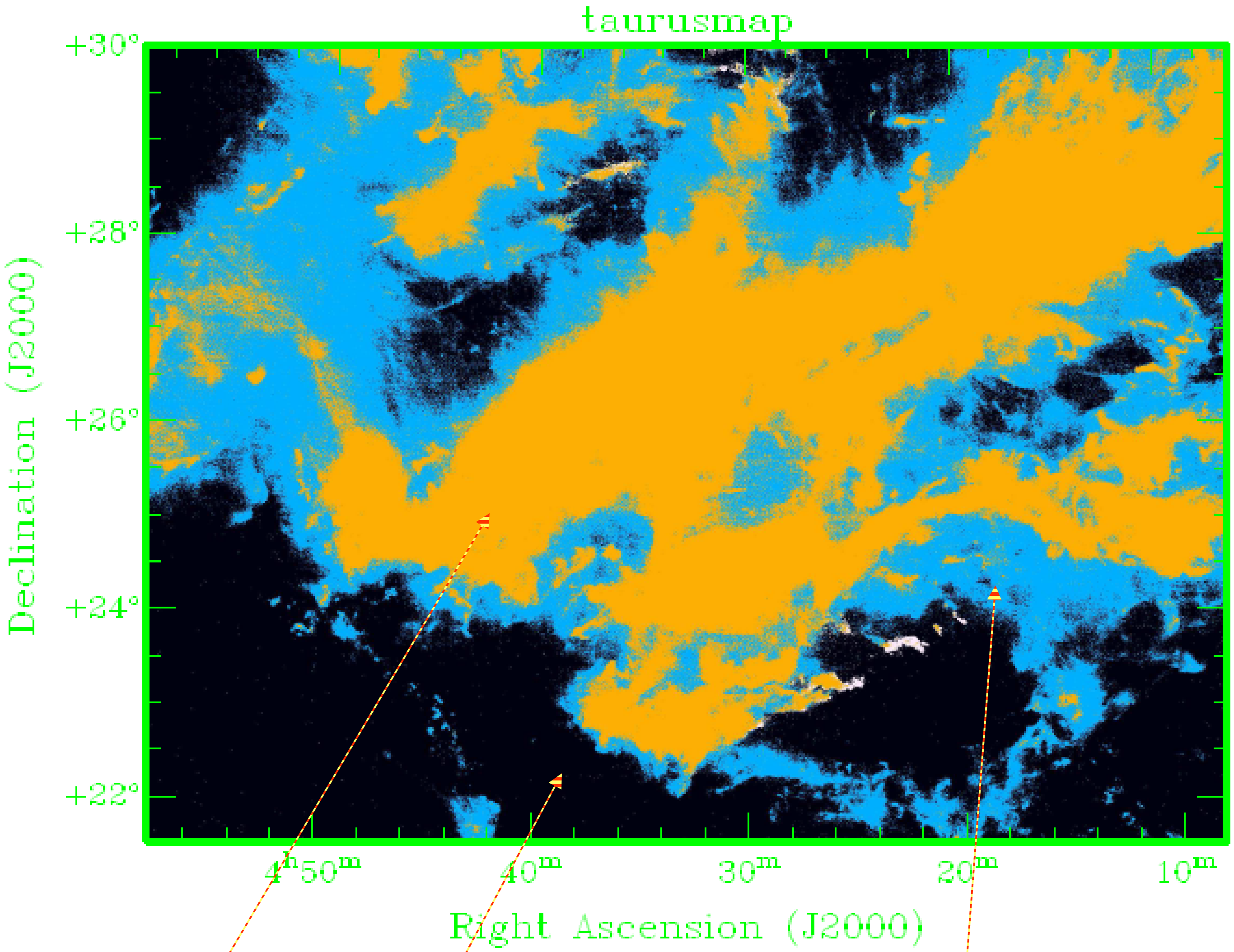
Studying molecular clouds = “blobology”

FCRAO Map 50” beam Nyquist-sampling => $3x10^6$ pixels



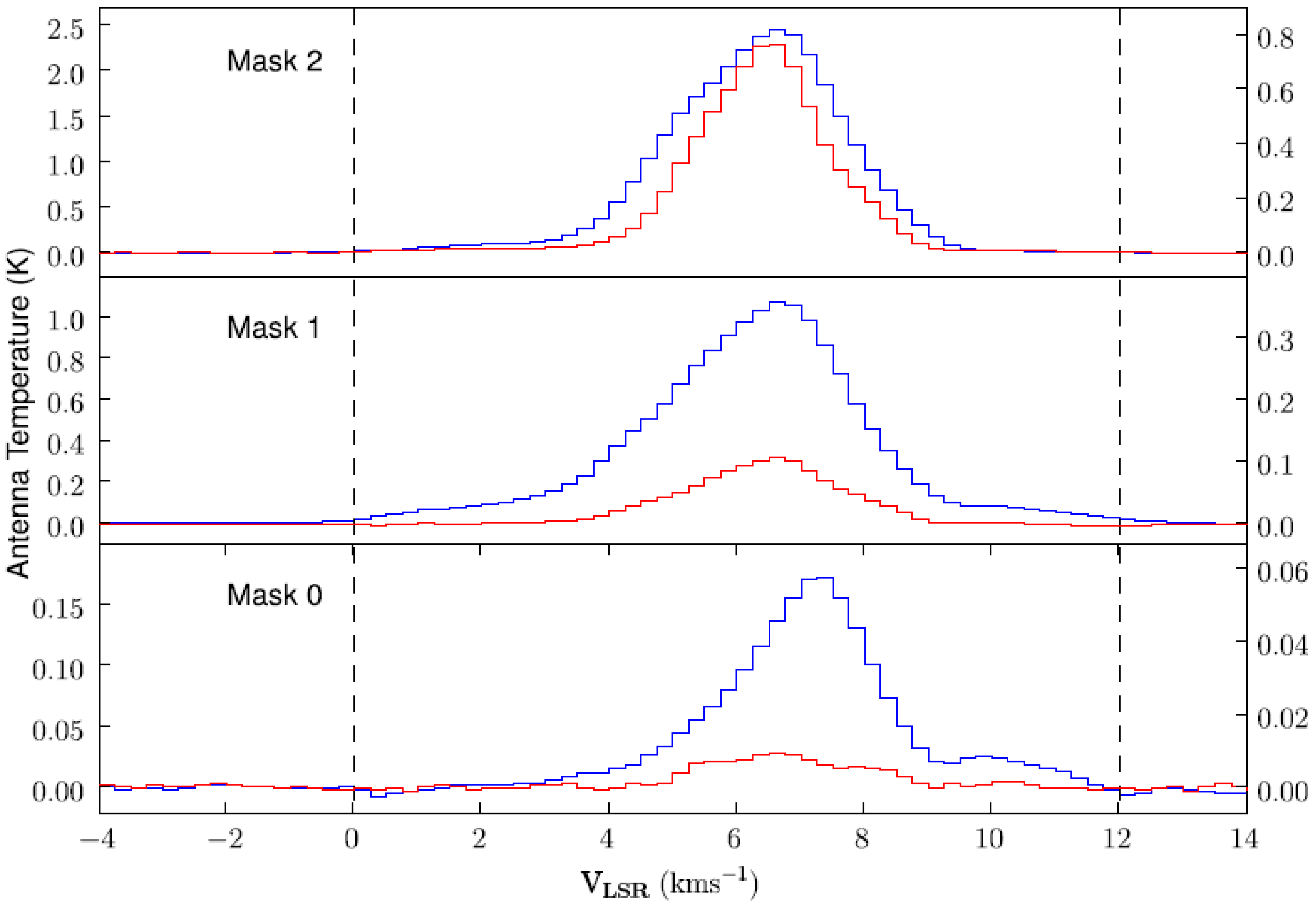
FCRAO Map 50” beam Nyquist-sampling => $3x10^6$ pixels





Mask 2 ^{12}CO & ^{13}CO detected in pixel; Mask 1 ^{12}CO but not ^{13}CO detected; Mask 0 neither isotopologue detected

Average Spectra in Each Mask Region



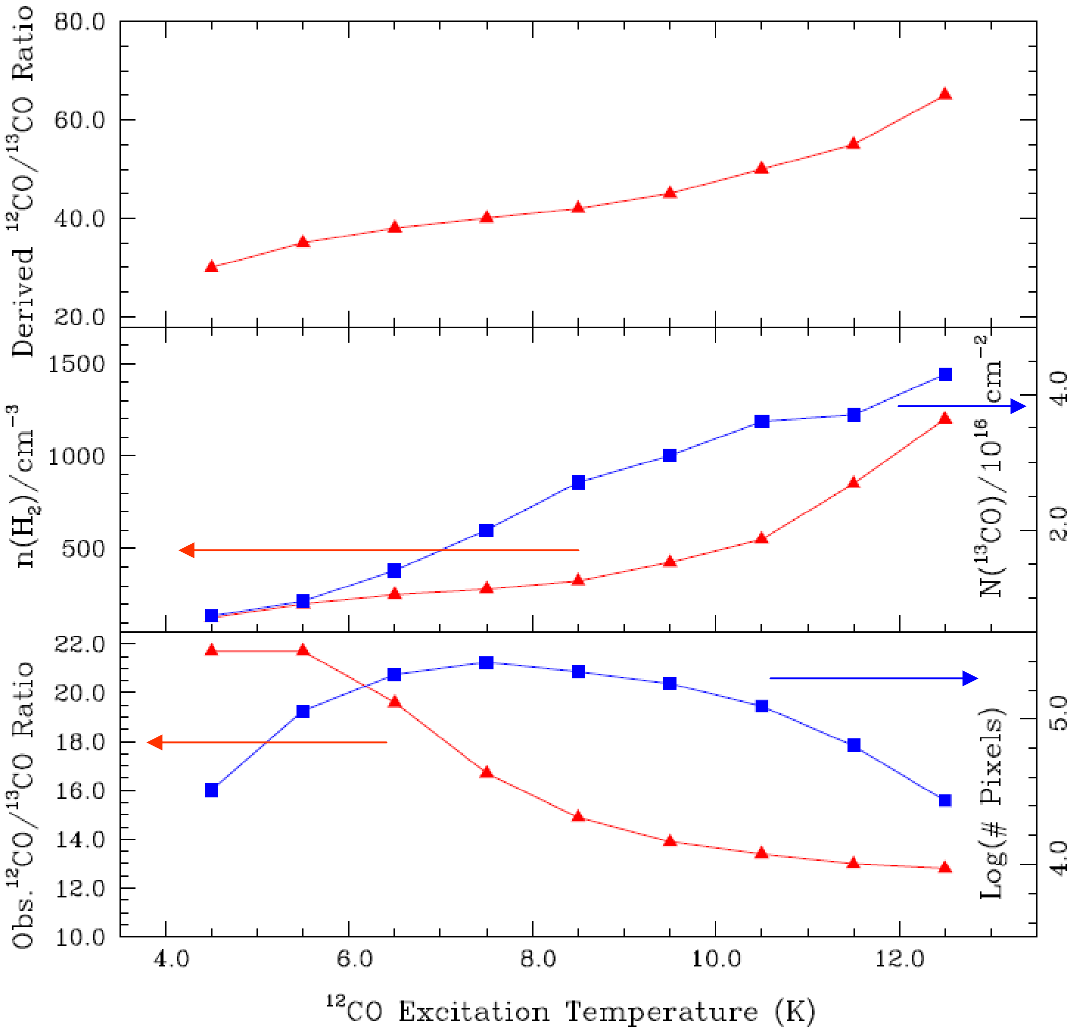
Mask 2 Data

- Both isotopologues in each pixel (“standard” cloud mapping situation)
- Find T_{ex} from max $\{^{12}CO\}$
- Assume LTE so this directly yields T_{kin}
- Determine $\tau(^{13}CO)$, R $(^{12}CO/^{13}CO)$ and thus the column densities of both isotopologues

Dealing with Mask 0 and Mask 1 Data

- **Bin** pixels by excitation temperature and average spectra within each bin
- ^{13}CO as well as ^{12}CO then detected (30,000 – 200,000 pixels in each bin)
- Use data for both isotopologues with LVG model to determine $n(H_2)$ and N(CO) per bin
  T_{kin} specified to be 15 K
- The result is relationship between N(CO) and T_{ex} and thus between $T(^{12}CO)$ and N(CO)

Behavior of Mask 1 Pixels

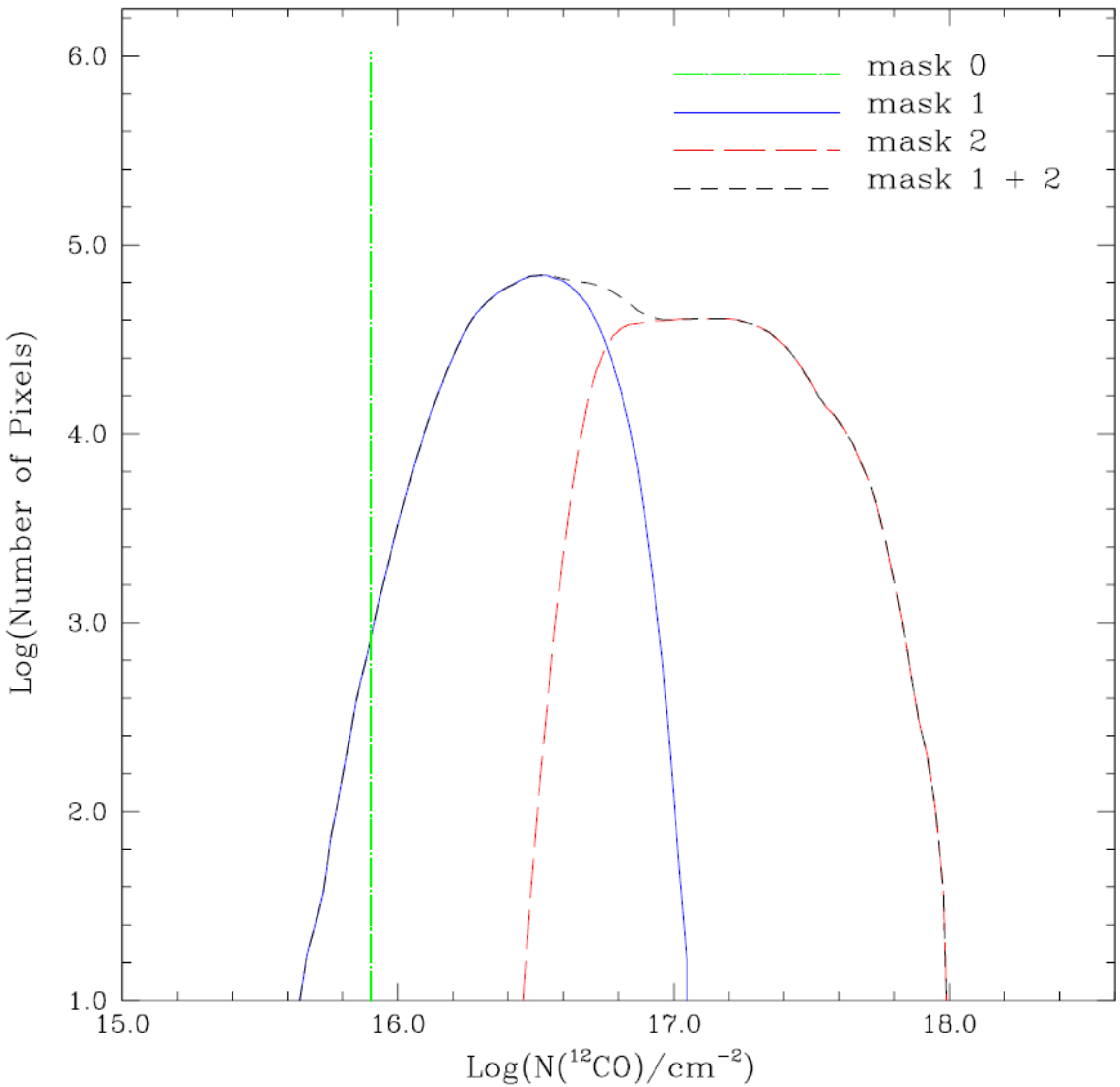


Derived $^{12}CO/^{13}CO$ ratio increases with increasing T_{ex}

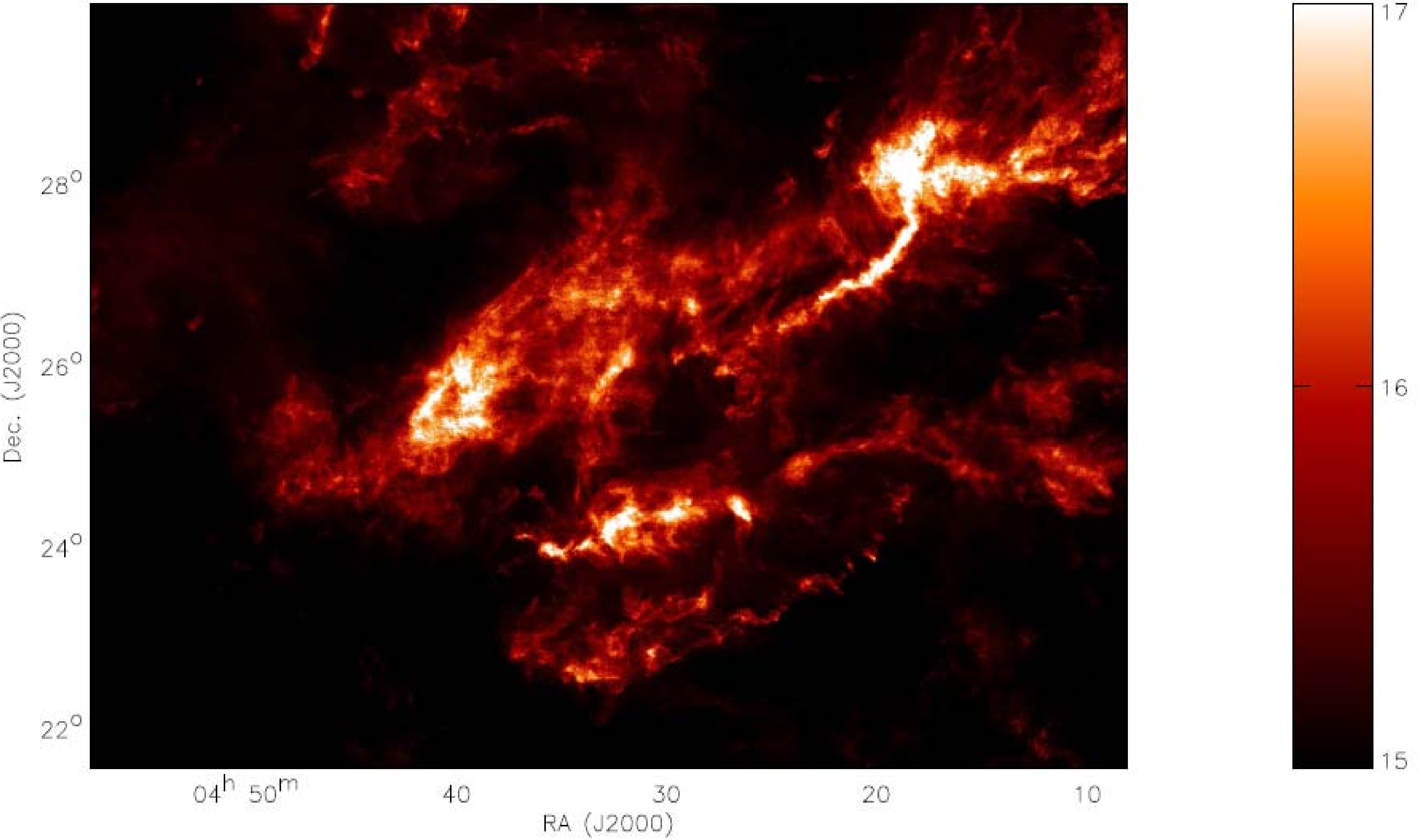
$n(H_2)$ decreases for lower T_{ex} due to subthermal excitation

Observed $^{12}CO/^{13}CO$ ratio drops with increasing T_{ex}

Distribution of CO Column Densities



^{12}CO Column Density Image



Conversion to H_2 Column Density

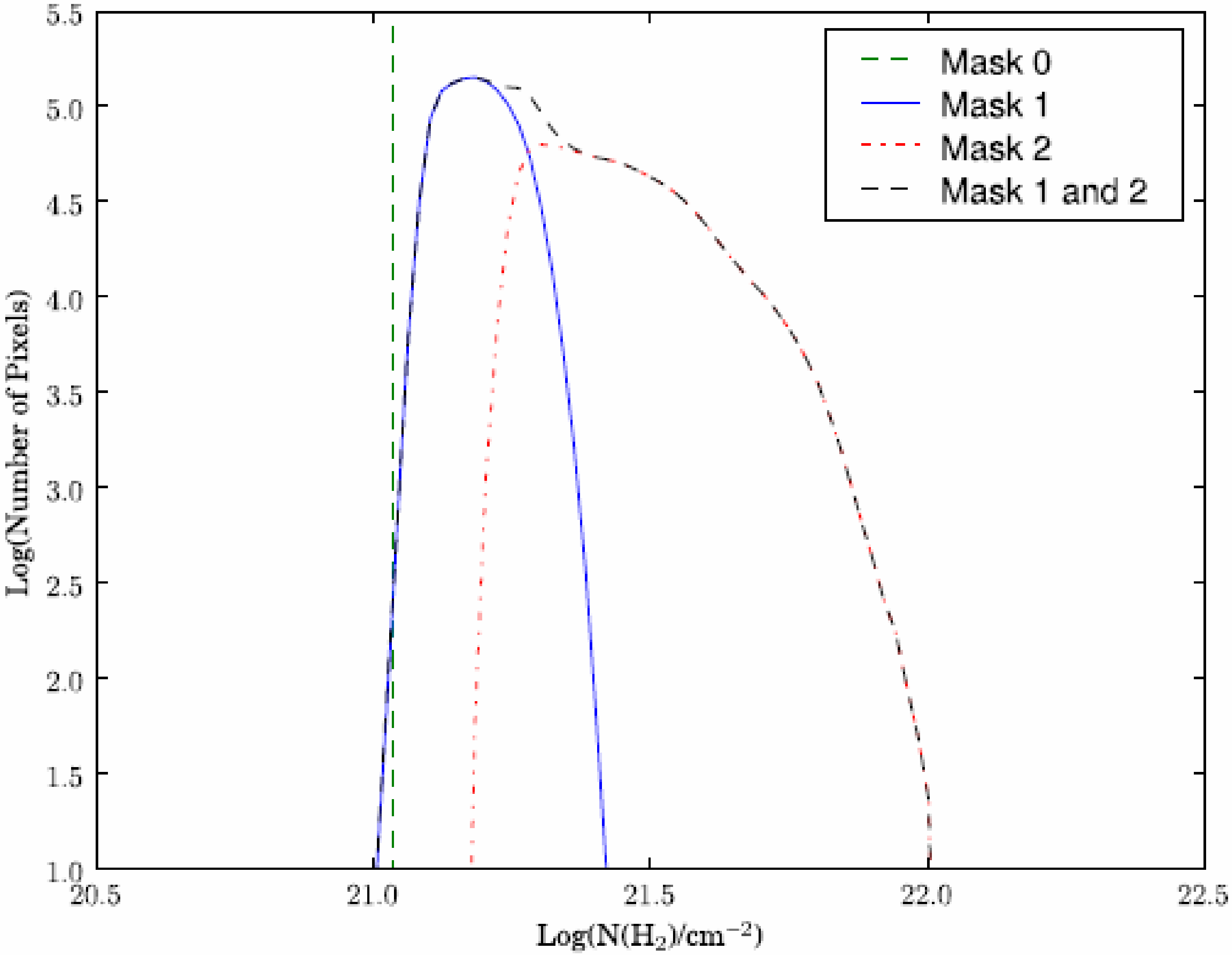
Region mapped includes a very large range of column density and thus of visual extinction

Use of single fractional abundance for CO is almost certain to be seriously in error

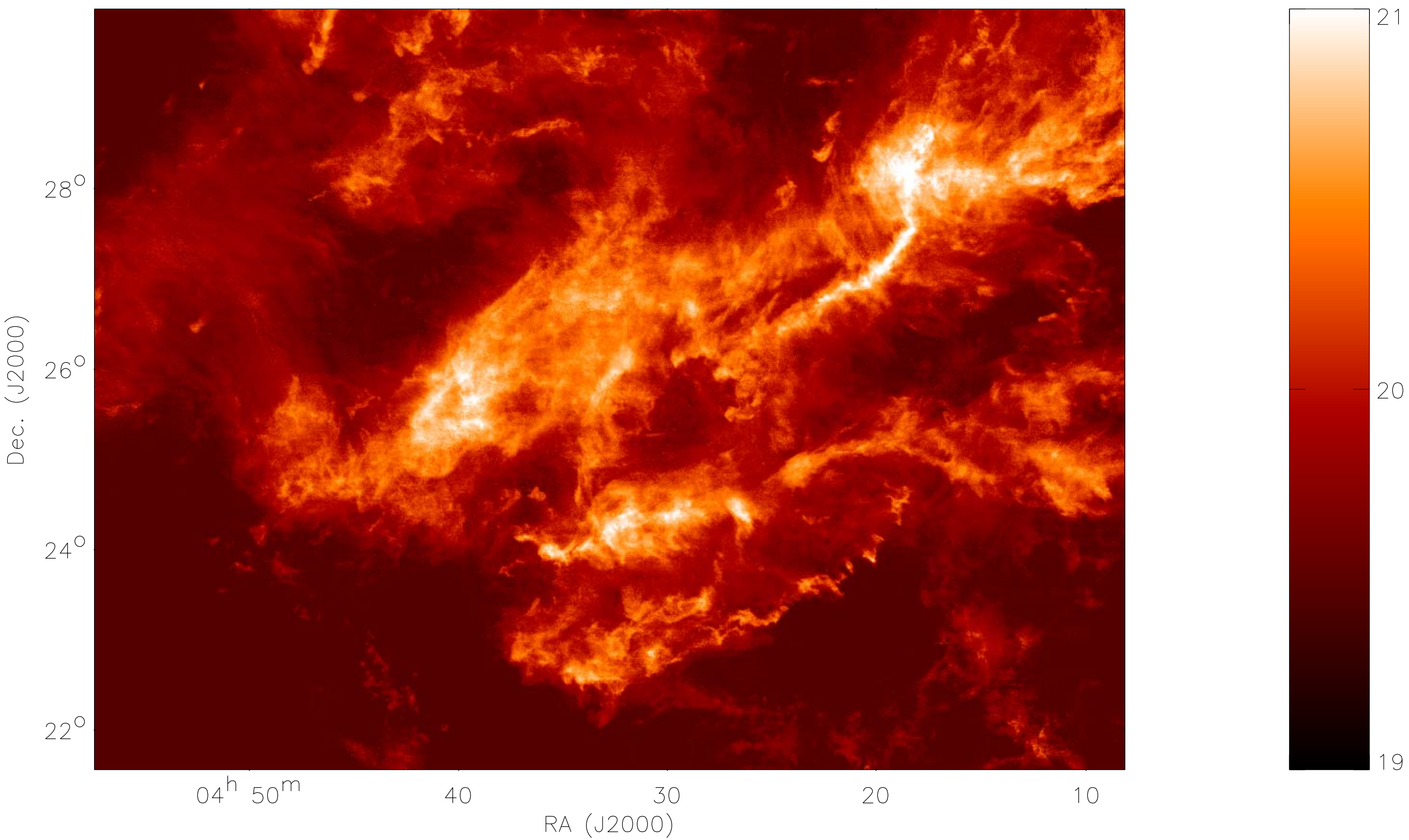
Adopt model from VanDishoeck & Black (1988) optimized for Taurus, which calculates N(CO) as fn. of $N(H_2)$; we invert the process to get $N(H_2)$ from N(CO)

X(CO) varies from ~ 10^{-6} in mask 0 to 10^{-4} in high-A_V portion of mask 2

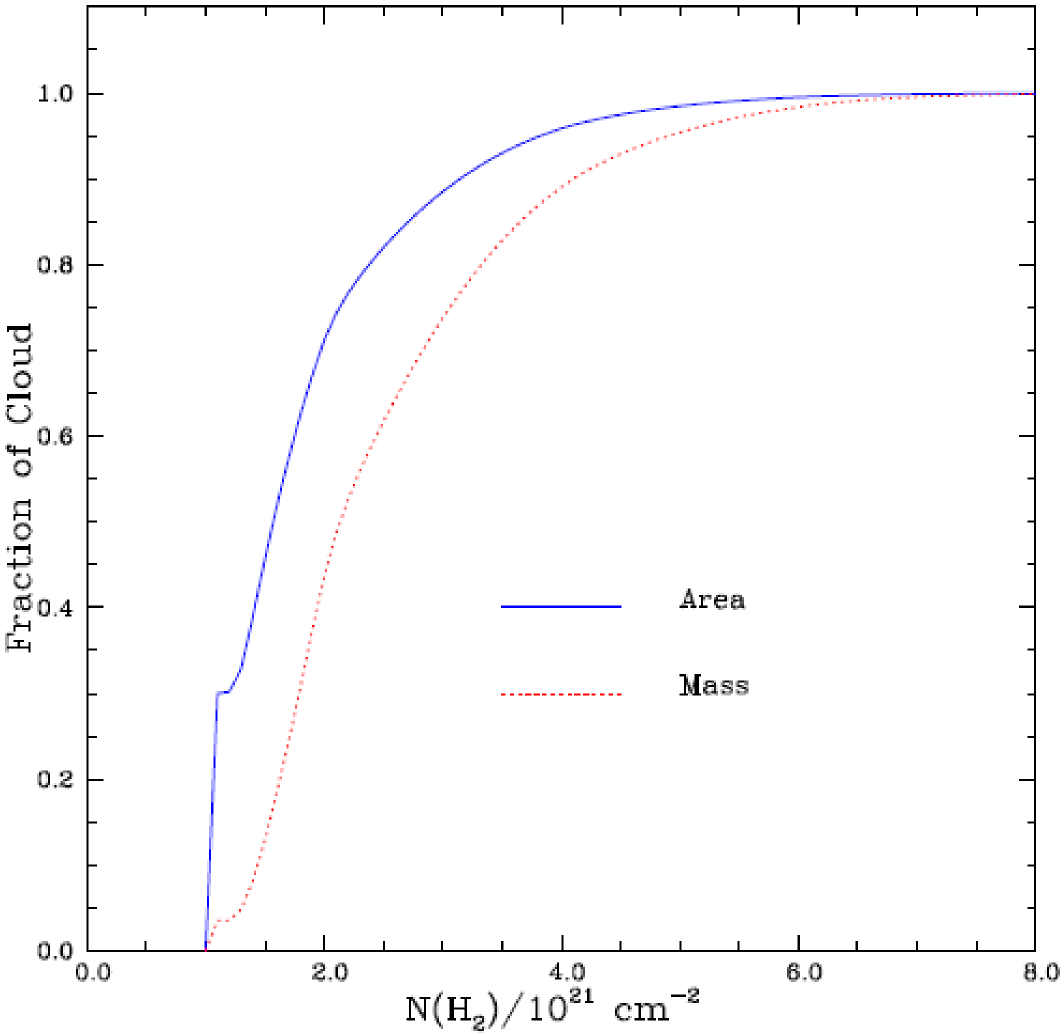
Histogram of $N(H_2)$ Distribution



H_2 Column Density Distribution in Taurus



Cumulative Distribution of Mass and Area



Lower CO Fractional Abundance in mask 0 and 1 Regions Greatly Increases Mass Determined In Our Analysis

Table 3. Mass of Region in Taurus Mapped

Mask Region	Mass ($10^3\ M_\odot$) a	b
0	0.1	4.1
1	1.7	7.7
2	7.8	11.8
Total	9.6	23.6

[a] Using constant H_2/CO ratio equal to 2×10^4

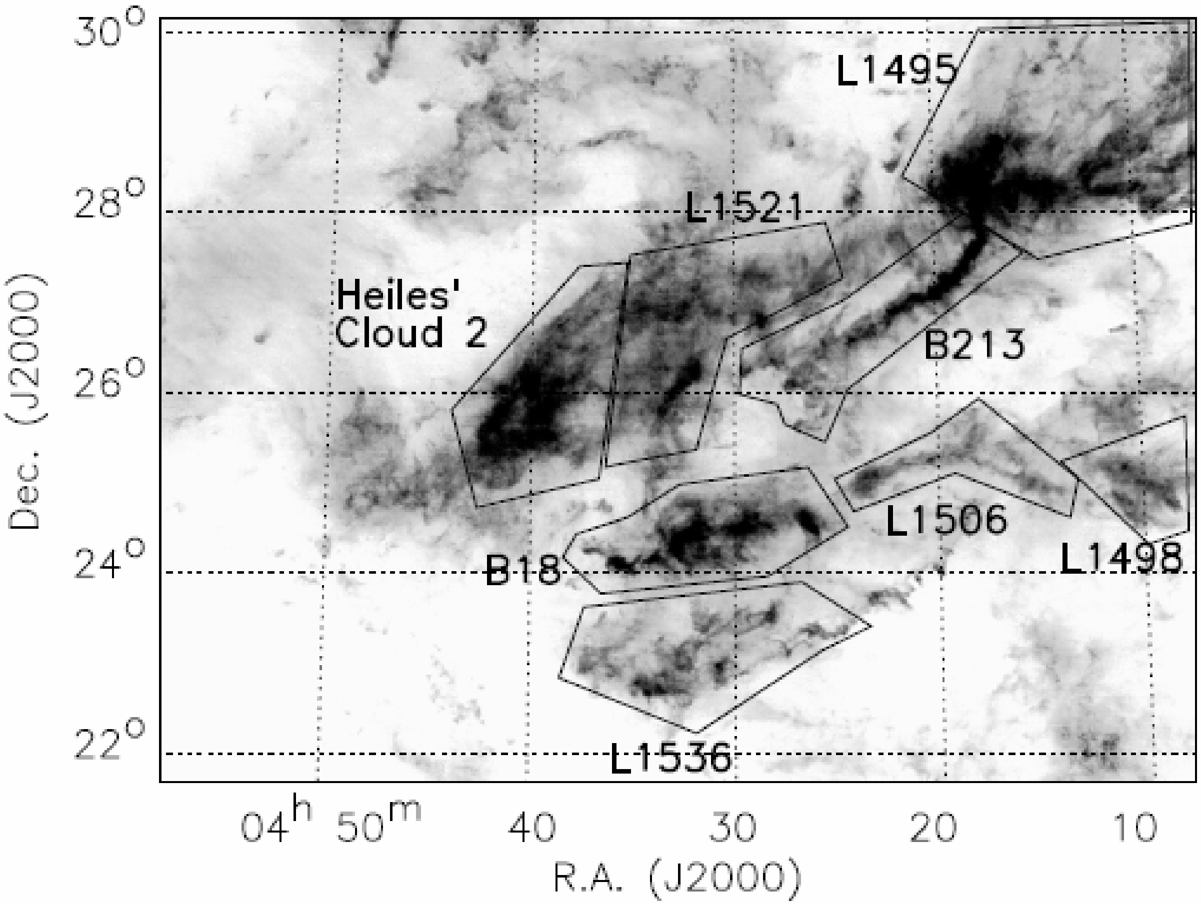
[b] Using H_2/CO ratio with I(UV) = 1.0 and $\delta_C = 0.1$ from Van Dishoeck & Black (1988)

Masses Determined with Variable X(CO) and Including Diffuse Regions Agrees well with those Found from L(CO)

Table 5. Comparison of Masses Determined from ^{12}CO and ^{13}CO With Those Derived from CO Luminosity

Region	Mass from ^{12}CO and ^{13}CO ($M_\odot$)	^{12}CO Luminosity ($\mathrm{K km s^{-1} pc^2}$)	Mass from ^{12}CO Luminosity ($M_\odot$)
mask 0	4081	193	791
mask 1	7699	2052	8413
mask 2	11752	3305	13550
Total	23532	5550	22754

Hitchiker's Guide to Taurus and Mass of High Density Regions



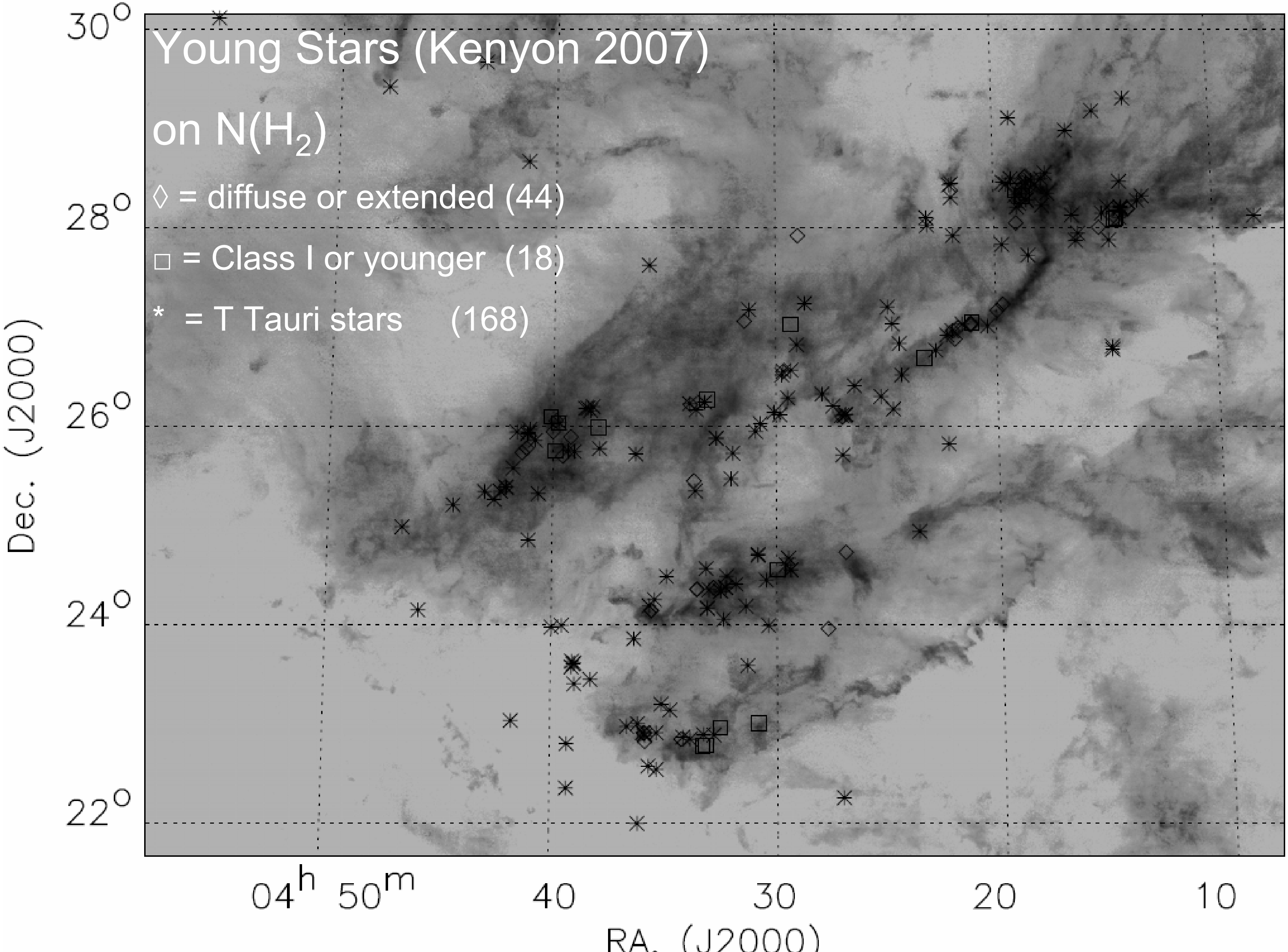
Mass of High–Density Regions in Taurus[a]

Region	Mass [b] $M_\odot$	Area pc^2
L1495	2616	31.7
B213	1095	13.7
L1521	1584	17.6
HCl2	1513	15.8
L1498	373	5.7
L1506	491	7.7
B18	1157	14.5
L1536	978	16.6
Total	9807	123.3

[a]Regions defined in Figure 11

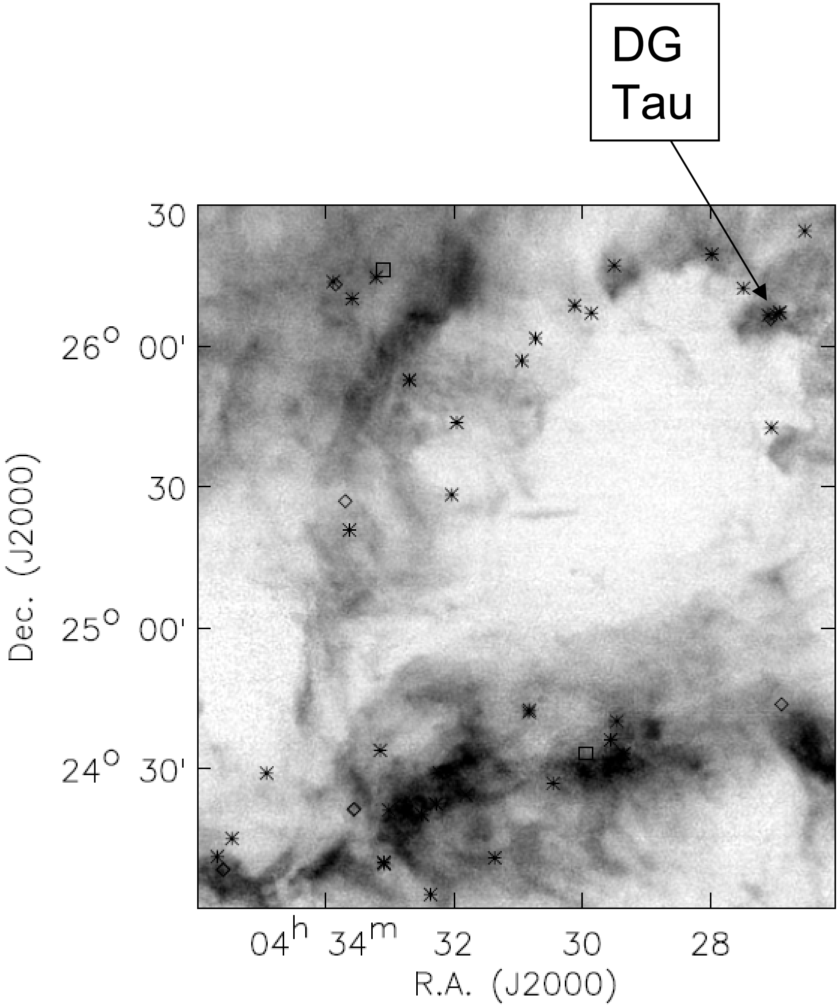
[b]Includes correction for He

Total Cloud Mass = 2.4×10^4 Solar Masses

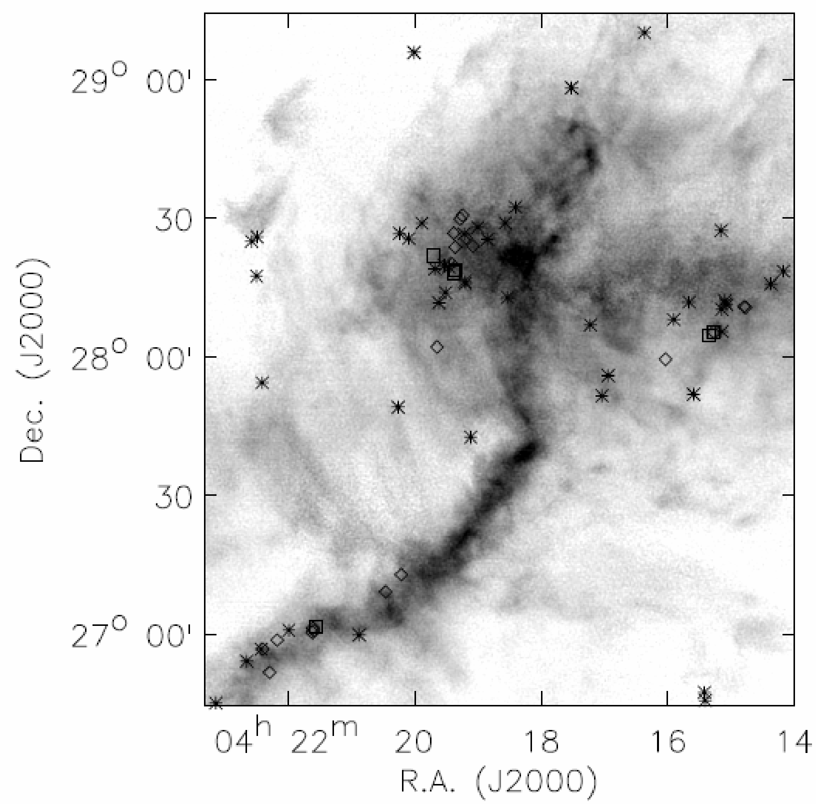


Young Stars (Kenyon 2007)
on N(H_2)
◊ = diffuse or extended (44)
□ = Class I or younger (18)
* = T Tauri stars (168)
30°
28°
26°
24°
22°
Dec. (J2000)
04h 50m
40
30
20
10
RA. (J2000)

Enlarged Images of Some of the Regions with Numerous Young Stars

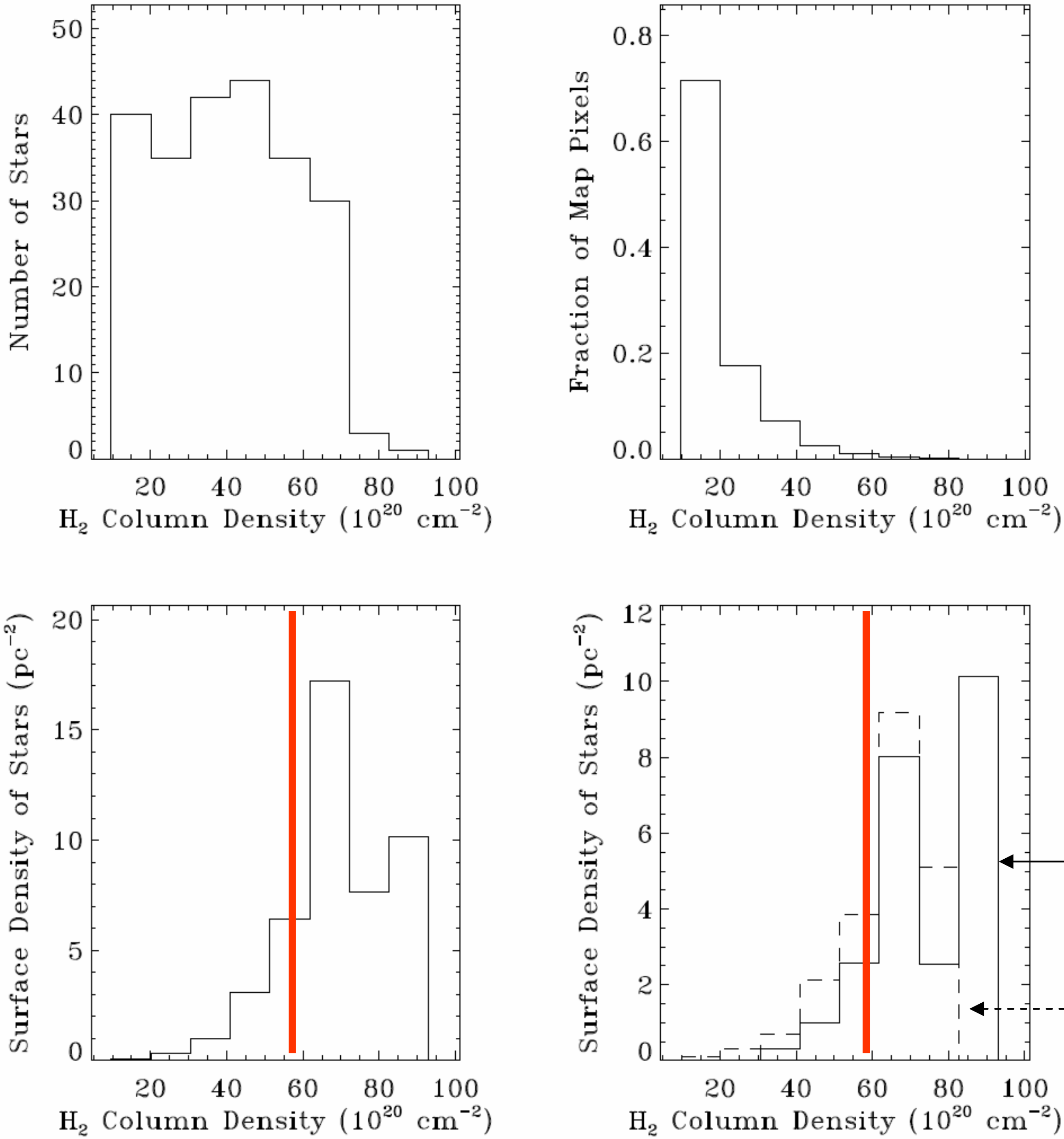


Cavity and B18



L1495 and B213

Young Stars in Taurus and H_2 Column Density



Column Density Threshold for Star Formation

Class I or diffuse/extended

T-Tauri stars

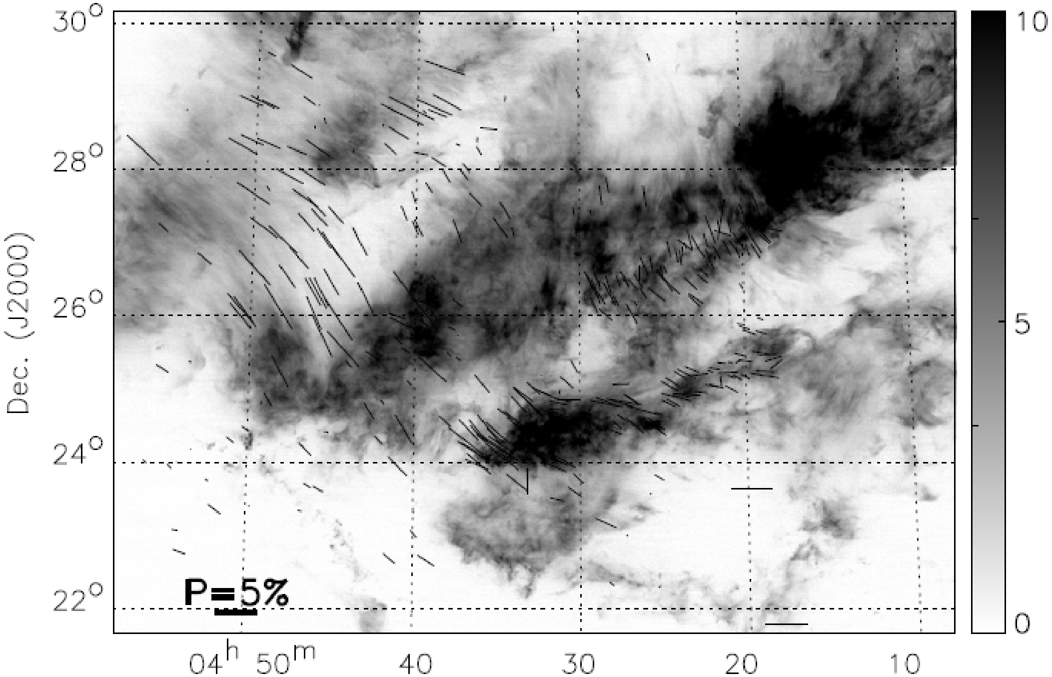
Star Formation Efficiency (SFE) and Star Formation Rate (SFR)

3 definitions of SFE using $\langle M_{star} \rangle = 0.6 M_{sun}$ (Palla & Stahler 2002)

1. **Overall**: Total stellar (230) mass / total gas mass = 0.006
2. **Current**: Protostar (Class I & embedded) mass / **dense gas** mass = 0.003
3. **Pragmatic**: PMS star mass / dense gas mass = 0.012

- Avg. SFR over past 3Myr ~ $5 \times 10^{-5}\ M_{sun}$/yr
- Avg. SFR ~ $2 \times 10^{-9}\ M_{sun}$/yr per M_{sun} of molecular gas

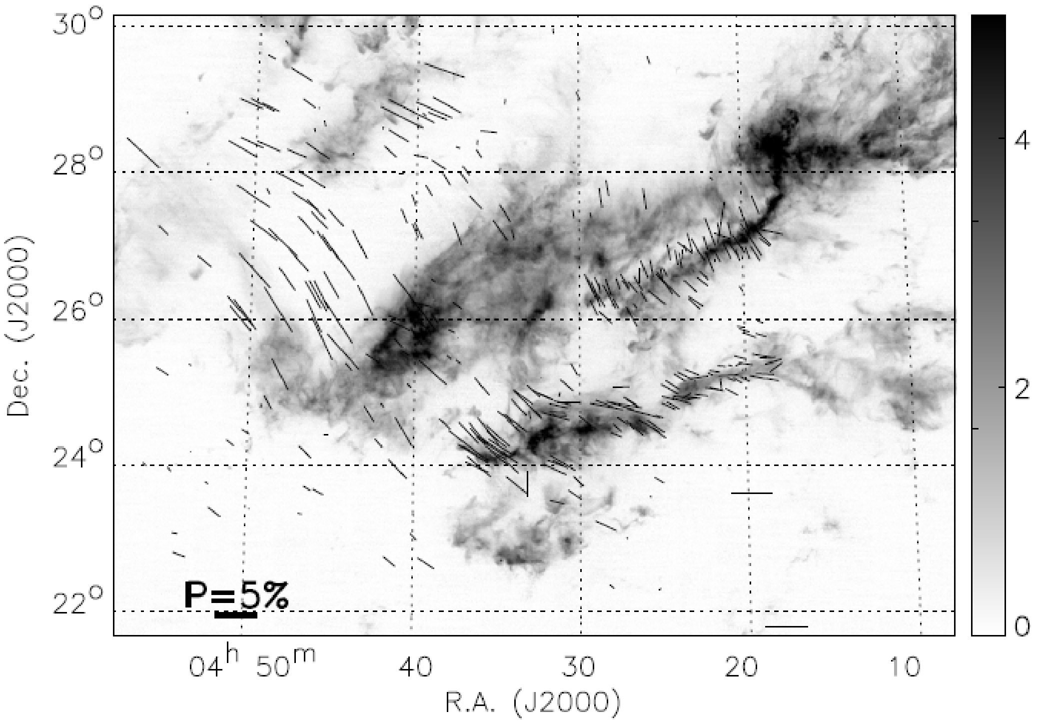
Low SFE and SFR due in part to low fraction of dense gas at high column density



Magnetic Field Direction & Fractional Polarization

Superimposed on ^{12}CO integrated intensity (5 km s^{-1} to 8 km s^{-1})

Striations in low-N region in NE follow field lines

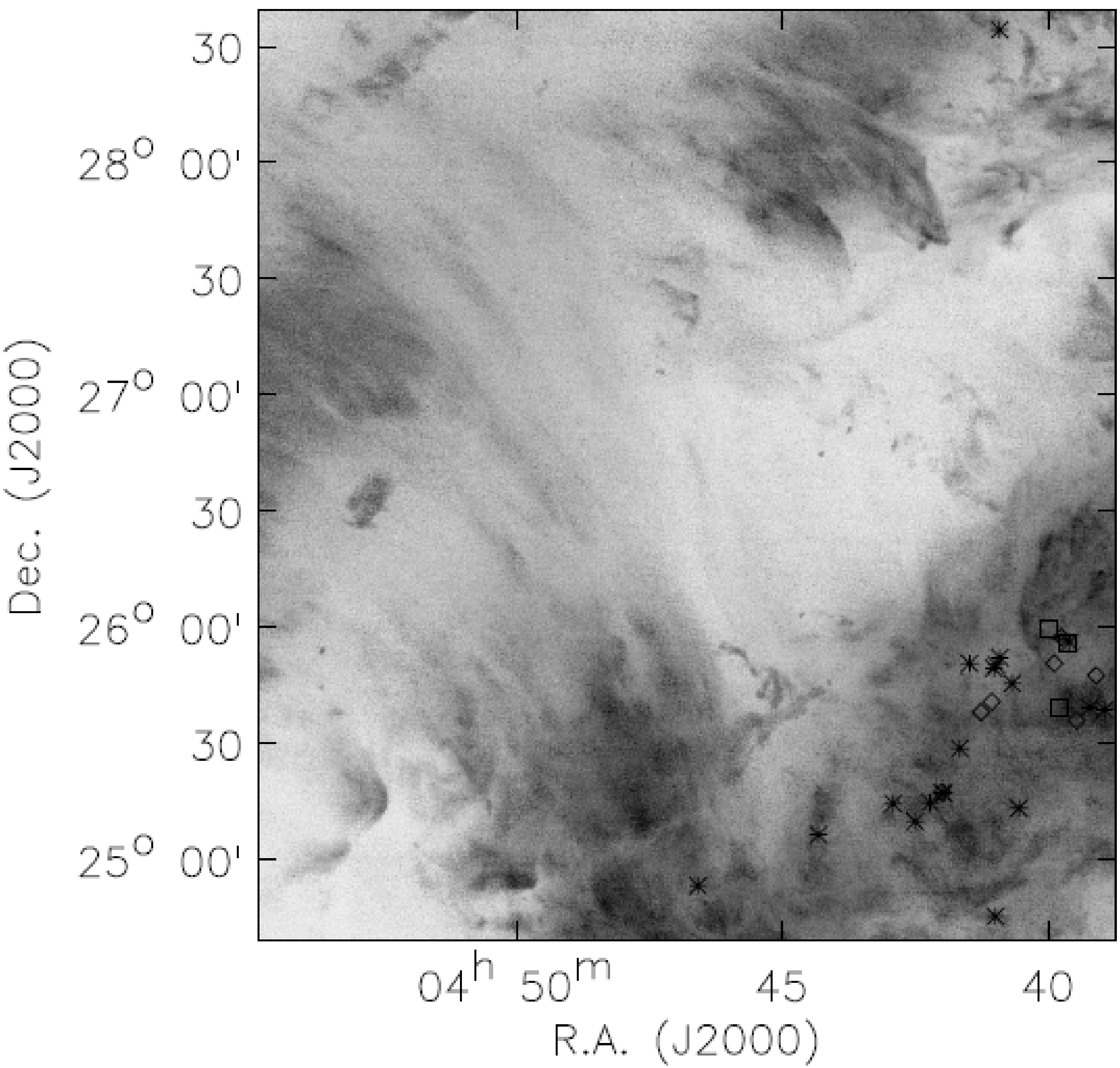


Superimposed on ^{13}CO integrated intensity (5 km s^{-1} to 8 km s^{-1})

B $\perp$ long axis of B213 filament

Orientation of B w.r.t. B18 and L1506 less clear

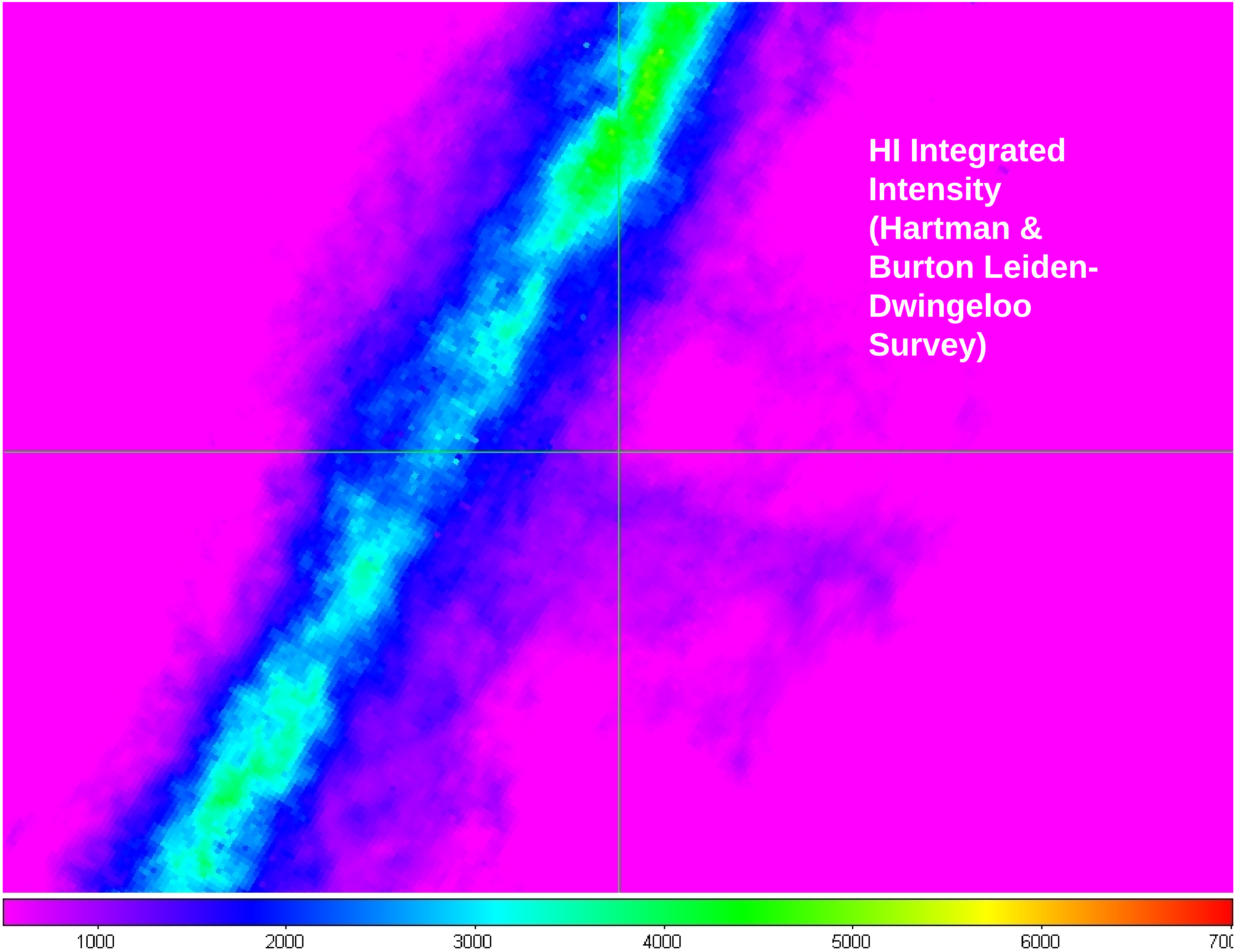
Caveat: B-field inferred from optical absorption measurements

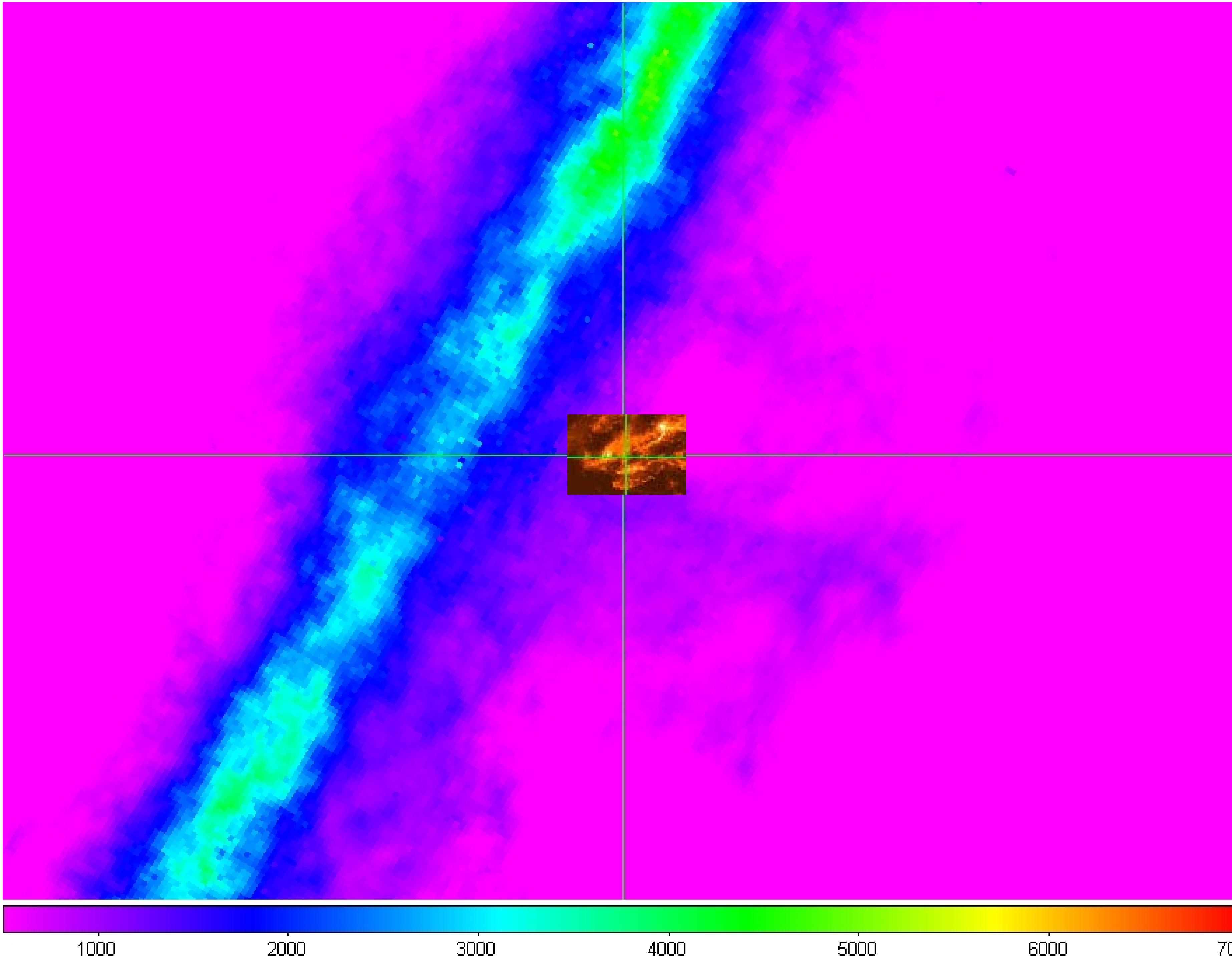


Striations in NE Region

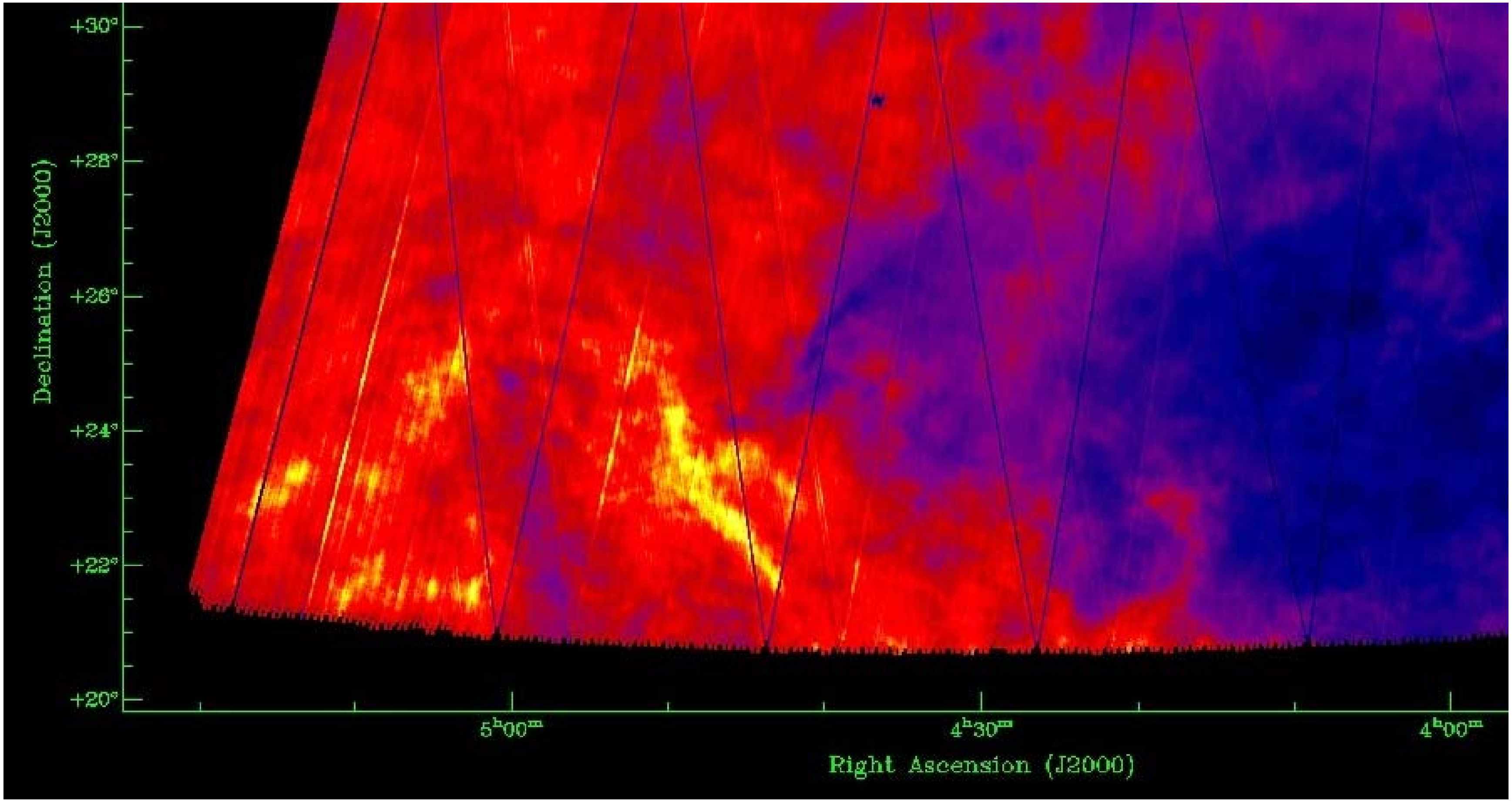
The End

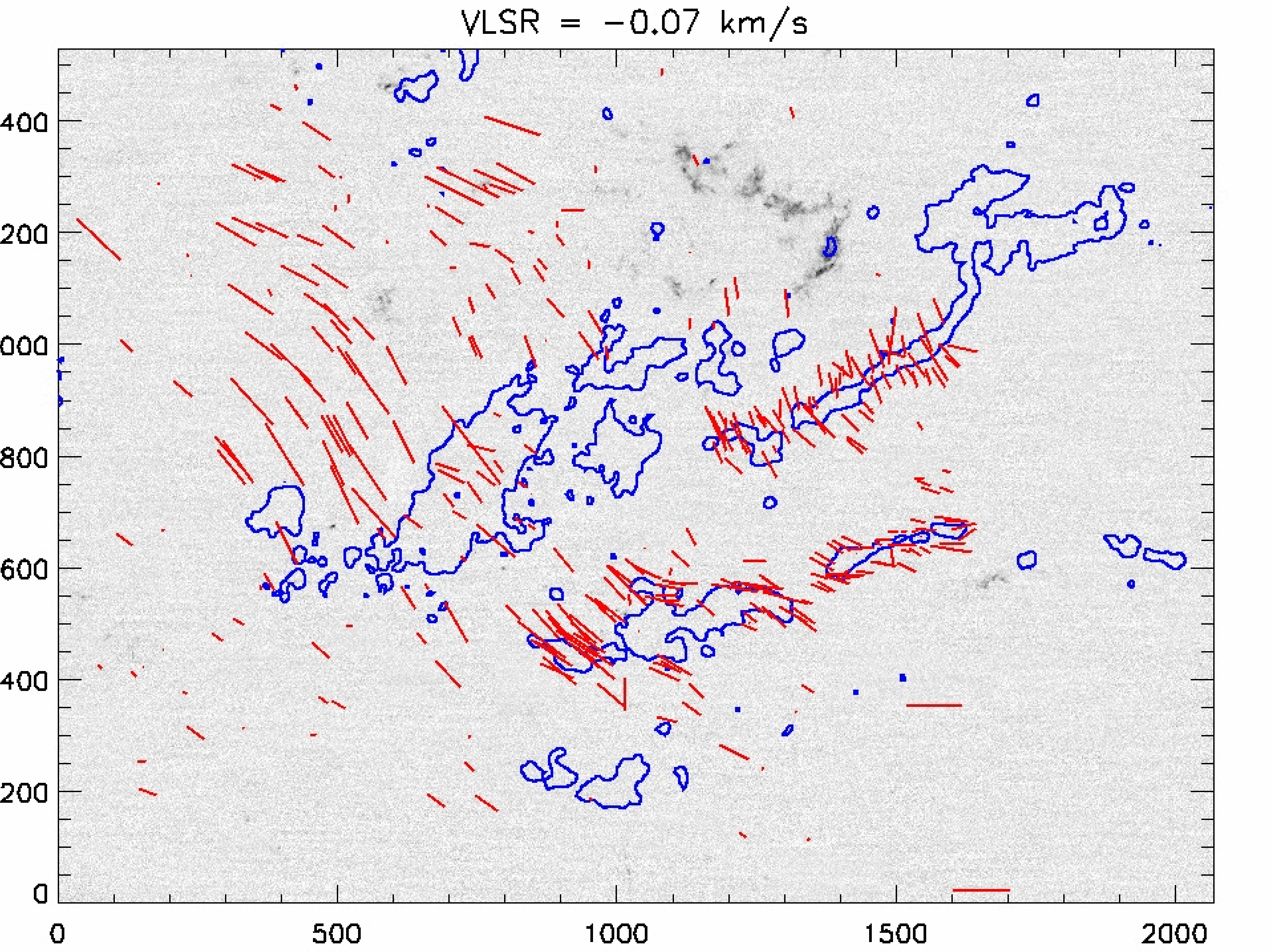
But there is much more that can be done with this data set


HI Integrated Intensity (Hartman & Burton Leiden-Dwingeloo Survey)
1000
2000
3000
4000
5000
6000
70(


1000
2000
3000
4000
5000
6000
700

HI from Arecibo GALFA Survey Image in 5 to 6 km s^{-1} Channel




VLSR = −0.07 km/s
400
200
000
800
600
400
200
0
0
500
1000
1500
2000