Wide-Field Line Ratio Analysis: High Dynamic Range Column Density Maps of the Milky Way

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Threads

1. **Nature of the problem**, i.e. going from T_b to $N_{col}/T_{ex}/\tau$

2. Ongoing projects:

- a. ThrUMMS, three iso-CO $f=I\rightarrow O$ lines, very large contiguous area = 120 deg², including lessons from CHaMP
- b. ¹³CO with SEDIGISM $\tilde{\mathcal{J}}$ =2→1 and ThrUMMS $\tilde{\mathcal{J}}$ =1→0, large overlap $area = 60 deg²$
- c. SEDIGISM¹³CO + $C^{18}O$ \tilde{f} =2→1, only possible over small areas (-0.01 deg^2) where $T_b(C^{18}O) \ge 2^-3$ K

3. Future projects:

- a. Mutually reconciling 2a–2c, e.g. abundance variations, non-LTE conditions
- b. Connecting τ , T_{ex} , N_{col} cubes to SCIMES catalogues, Galactic structure, other topics (eg, CODEX project with GUSTO mission)

How do we turn data into fundamental physics? E.g., molecular mass + excitation, detailed comparisons with cold dust?

Figure 2. The iso-Co ratio-ratio-ratio-ratio-ratio-ratio-ratio-ratio-ratio-ratio-ratio-ratio-ratio-ratio-ratio- R_{max} R_{max} R_{max} The Basic Problem

brightness temperature:

 $A + O$ \sim UDSCIVE Observe line emission

 \Box

the integrated intensities in the 3 lines, for each Region

and separate velocity component, plus 3-colour overlays

for position-velocity (PV) maps as well. A sample (*l*,*b*)

 $t_{\rm 13C}$

brightness to the ¹²CO, which indicates higher opacity

and/or lower excitation. This is true for both the (*l*,*b*)

This colour presentation gives us an intuitive feel for

mosaic for Regions 9–11 is shown in Figure 1.

$$
\text{sion} \quad \boxed{T_{\text{mb}} = [S_{\nu}(T_{\text{ex}}) - S_{\nu}(T_{\text{bg}})](1 - e^{-\tau})}
$$

13, and *R*18 in the basic physics is in the basic physics in the basic physics is in the basic physics in the basic physics is in the basic physics in the basic physics in the basic physics in the basic physics in the bas

used for various diagnostics and studies of stellar pho-

The Text is a time we have result to the SMC Text is a single line we have result to $\frac{1}{2}$ *results to* $\frac{1}{2}$ *results to* $\frac{1}{2}$ where a single inte, we have 1
equation with 2 unknowns, τ and T_{ex} : the relevant antenna eciencies, *T*bg = 2.726 K is the vocal vocality be the region of the term o τ and I_{ex} : With a single line, we have 1 equation with 2 unknowns,

CHaMP IV. Molecular Clump Dynamical Evolution 5

the line ratio analysis to follow. By rendering the ¹²CO * We want physical quantities,

like mass distribution
 $\bigcup_{x \in \mathbb{R}^n} \bigcup_{x \in \mathbb{R}^n} \bigcap_{x \in \mathbb{R}^n} \bigcap_{x$ like mass distribution, high excitation cosmic background temperature, and the source function as Planck is a planck of the Boltzmann state of the Boltzmann show the Rayleigh-Jeans approximation to *S* in the secexcitation conditions quantities in the optical and near-IR. \mathbb{R} for any species one of the same via \mathcal{A}

 \ddotsc the \ddotsc **Emissivity ≠ Mass** appear blue than average significant than average significant enterprise \mathcal{L} (see later)

Hammed For the Quo vadis?

Mass
$$
N = \frac{3h}{8\pi^3\mu^2} \frac{Q(T_{\text{ex}})e^{E_u/kT_{\text{ex}}}}{J_u(e^{h\nu/kT_{\text{ex}}}-1)} \int \tau dV
$$

of molecular clouds near the solar circle (Giannetti et al.

where $\overline{}$ is the model model

tional partition function, *E^u* and *J^u* are the energy and

 α), including the Carina Arm of the Carina Arm of the Carina Arm of the Milky and the Milky

ThrUMMS: a "simple" example eithe 13CO or CNO appear bluer or greener than average signify χ show the Rayleigh-Jeans approximation to *S* in the seco "imple" organizato a simple cxample also assume that all CHaMP clouds have a single abun-

- For *J*=1→0, have ¹²CO, ¹³CO, and C¹⁸O data, so 5 equations (3 radxfer + 2 abundance ratios R_{13} , R_{18} connecting species) in 9 unknowns: $3\times\tau$, $3\times T_{\text{ex}}$, $3\times N_{\text{col}}$ \downarrow T γ and \downarrow \star For $j=1$ \to 0, have and PV images. The renderings in the α connecting speci Ω , ¹³CO, and C¹⁸O data, so 5 \cup , \cup , and \cup \cup data, so, κ explanation by κ κ κ κ κ κ κ It 9 UHKHOWHS: 3×1 , 3×1 ex, 3×1 vcol
- Assume single, common T_{ex} (LTE) and R_{13} = 60 (both reasonable) so 3 more \rightarrow 8 equations are more average, *I*18/*I*¹³ ⇠ 0.2, *I*13/*I*¹² ⇠ 0.5, although t^* **Assume single, C** F_{e} $\frac{1}{2}$ \overline{T} (ITE) as \overline{D} (c) that $\text{min } I_{\text{ex}}$ (LIE) and K_{I3} = 00 (DOM) $e \rightarrow 8$ equ The result is that we can evaluate not only the op-
- * Final relation: τ_{12} >>1, giving (e.g.) $T_{ex} \approx T_{mb}$ ⁽¹²CO)+2.73 t_{12} that relation. t_{12} oivino (e σ) $T_{\text{or}} \approx T_{\text{mb}}(12 \text{CO}) + 2.72$ σ cubes, but also the influence σ $\overline{}$
- * Now solve directly: \sim 1 YOW SOLVE GLICE abundance ratio at every coordinate, via

blue, clumps which have a relatively low opacity and/or

high excitation will appear \mathcal{L}

can also see that clumps BYF 73, 77, and 111 (the bluer

opacity in the ¹²CO line, *T*ex is well-traced by the ¹²CO

Side benefit: in this case, even compared to their neighbours. column density is very $HDR (high dynamic)$ HDR (high dynamic range) effectively peeling away $thaico-COlavore$ the iso-CO layers where the subscripts 12, 13, and 13, and 13, and 18 refer to the 18 refer to the 18 refer to the *T*mb, 13, and 13, an

$$
\frac{T_{13}}{T_{12}} = \left[\frac{S_{13}(T_{\text{ex}}) - S_{13}(T_{\text{bg}})}{S_{12}(T_{\text{ex}}) - S_{12}(T_{\text{bg}})}\right] \frac{1 - e^{-\tau_{13}}}{1 - e^{-R_{13}\tau_{13}}},
$$
\n
$$
\frac{T_{18}}{T_{13}} = \left[\frac{S_{18}(T_{\text{ex}}) - S_{18}(T_{\text{bg}})}{S_{13}(T_{\text{ex}}) - S_{13}(T_{\text{bg}})}\right] \frac{1 - e^{-\tau_{18}}}{1 - e^{-\tau_{13}}},
$$
\n
$$
\tau_{12} = R_{13}\tau_{13}, \text{ and}
$$
\n
$$
\tau_{13} = R_{18}\tau_{18},
$$

and *S* of the relevant isotopologue. With *T*ex from Eq. 1,

as Planck's and Boltzmann's constants, respectively. We

Eyeball physics (with Dylan Barnes): lots of cold (low *T*ex), opaque (high τ) clouds, high N_{CO} rare (B+2021, in prep.)

SCIMES Analysis

ThrUMMS Sector: 330°-336° $13CO(1-0)$ $(dv=-150-50 km s^{-1})$

Intensity Based Extraction:

- \cdot 2.5 σ detection limit
- 4σ minimum separation difference

Column Density Based Extraction

(with Sebastian Lopez, B+2021, in prep.)

Mass distribution is much clumpier than emission distribution $I \neq N$

Thousands of clouds!

Other lessons from CHaMP

Use *Herschel* data to compute dust-based *N*H2 map

Derive [12CO]/[H2] abundance map: it's mostly *much lower* than expected, and varies *a lot* too!

¹²CO abundance law

16 Pitts & Barnes 2021 Parties 2021 Parties 2021 Parties 2021 Parties 2021 Parties 2021 $log_{10}(N_{\text{CO}}/N_{\text{H2},\text{dust}}) = -10$ $[log_{10}(T_{\text{d}}/20.0 \text{ K})]^2 - 4.13$

- All CHaMP data (Paper V, Pitts & Barnes 2021):
- Median abundance \approx 7.4×10⁻⁵ per H_2 or about 1/3 canonical
- Caveats: LTE, GDR; otherwise, pretty straightforward

SEDIGISM: *slightly* messier

- With SEDIGISM, we also have *J*=2➝1 for 13CO + C18O: how does this help? Figure 2. The interpretation diagram (RRD), combining line ratios from the three data cubes for all of Regions 9–11 (covering the three data cubes for R
- 1st approach: combine 13CO *J*=2➝1 from SEDIGISM with ¹³CO 7=1→0 from ThrUMMS: $\mathcal{L} = \mathcal{L} = \mathcal$ * ISt approach: combine ¹³CO *f*=2⁻¹ from SEDIGISM derive the total CO mass distribution, and a dynamical brightness temperature:

analysis of the clump envelopes relative to their interi-

ors. We begin, however, with composite colour images of

the integrated intensities in the 3 lines, for each Region

dition the 12CO line will be significantly brighter than the 12CO line will be significantly brighter than the 1

$$
2x \to \left[T_{\rm mb} = [S_{\nu}(T_{\rm ex}) - S_{\nu}(T_{\rm bg})](1 - e^{-\tau}) \right]
$$

show the Rayleigh-Jeans approximation to *S* in the sec-

- Then we have to iteratively solve for the 2 lines' τ and common T_{ex} (2 equations in 3 unknowns) by connecting them through detailed balance: $\tau_{2-I}/g_2 = (\tau_{1-O}/g_1)e^{-\hbar v_{2-I}/kT_{\text{ex}}}.$ $*$ Then $*$ for positive \mathbf{F} is the property (*l*) mosaic for Regions 9–11 is shown in Figure 1. the line ratio analysis to follow. By rendering the ¹²CO ⇡ (*T*ex *T*bg) *,* ⌧ 1 and *h*⌫ ⌧ *kT,* where the optical depth is the optical depth in the line, $\frac{1}{2}$
- * Equivalent to iteratively solving for 2 versions of *N*, and matching them, as in Schuller et al 2017: high excitation will appear reddish, since in either concosmic background temperature, and the source function *S* iteratively solving for 2 versions of N, and $\frac{1}{2}$

Iterative Approach 71 *h*⌫ *^k* (*f*Tex *^f*Tbg)(1 *^e*⌧*ul*). (5)

radiative transfer equation:

- In Test Field (TF, with Audra **Fig.** 15.5 K, and $\frac{1}{2}$ $\frac{1}{2}$ Hernandez):
- Form a ratio of two *N*s calculated from each line, $\eta_{21}(T_{ex}) =$ then find T_{ex} where η =0 $\overline{\text{d}}$ $\overline{\text{d}}$ $\overline{\text{d}}$ $\overline{\text{d}}$ $\overline{\text{d}}$ $\overline{\mathsf{I}}$ $\overline{}$ $\overline{}$ $\log (\frac{N_{\rm tot,21}}{N_{\rm tot,10}}$ $\overline{\mathcal{A}}$ $\overline{}$
- Example 1: solvable voxel
- Example 2: not solvable $\begin{bmatrix} \frac{1}{2} & 16.0 \\ 0 & 1 \end{bmatrix}$ (more on next slide)
- Most (well, ~half) voxels solvable for τ_{2-I} , τ_{I-O} , T_{ex} , and N_{total} ⁽¹³CO)

sitions and produce unequal, possibly sub-thermal, excita-

Progress…

- Work is continuing (with Sebastian Lopez) using a faster Newton's method and cleaner algorithm than in TF
- The physics is nontrivial: even LTE modelling has intrinsic numerical issues…

Line Ratios are … Interesting

- ~Half the voxels have very low T_2/T_1 ratio: subthermal(?) excitation
- Convergence remains tricky, especially in low- $T_{ex}/$ high- τ DSD (double solution domain) near subthermal limit
- Eventually, will need non-LTE analysis for new physics

Unexpected Results

Of the voxels which have LTE solutions, most are high opacity $(\tau_{2^{-1}} = 0.4-4)$ and low excitation $(T_{ex} = 6-9)$ K)

* Assuming $\tau \ll 1$ should be avoided

X factors and other questions

- Can also compute 13CO *X*factor: -flat with *I*(¹³CO) in TF, but probably only because of Central Limit Thm.
- $*$ X_{13} hides a multitude of sins, e.g. *no provision* for subthermal voxels!
- Inside & outside the TF, X_{13} varies regionally & globally; need to map its value
- Implications for Dark Molecular Gas & N_{H2}, extragalactic work, etc.

More Applications \mathbf{F} \mathbf{V} \mathbf{O} $t = \sqrt{1 + \frac{1}{2} \sum_{i=1}^{n} \frac{1}{i}}$ Λ ADDICATIONS tical depth in all lines at every (*l*,*b*,*V*) position in the

are more average, *I*18/*I*¹³ ⇠ 0.2, *I*13/*I*¹² ⇠ 0.5, although this varies somewhat from Region to Region $\mathcal{L}_\mathcal{S}$

This description is description is quantified with the same radiative \mathcal{L}_max

transfer analysis as performed by Barnes et al. (2015).

 $T_{\rm eff}$ is to assume, at each velocity channel and α

pixel (i.e., we do this calculation in 3D), that all lines are

even compared to their neighbours.

2nd approach: iteratively solve between SEDIGISM $J=2 \rightarrow I$ ¹³CO & C¹⁸O lines' τ & T_{ex} (again, 2 equations in 3 unknowns) the various Trumpler clusters (i.e., most of Region 10 $*$ 2nd approach $f = 2 + 1$ ³CO & C²O lilles $l \propto T_{\text{ex}}$ (again, 2 equations in datively solve between **SEDIGIS** $\overline{1}$ ratively solve between SEDTOT. *T*¹² *S*12(*T*ex) *S*12(*T*bg) ¹ *^eR*13⌧¹³ *,* (2)

$$
\boxed{\frac{T_{18}}{T_{13}} = \left[\frac{S_{18}(T_{\text{ex}}) - S_{18}(T_{\text{bg}})}{S_{13}(T_{\text{ex}}) - S_{13}(T_{\text{bg}})}\right] \frac{1 - e^{-\tau_{18}}}{1 - e^{-\tau_{13}}}}
$$

⌧¹³ =*R*18⌧¹⁸ *,* (5)

insensitive to this assumption; this insensitivity is also

illustrated in Figure 2 (see next) via grids for both *R*¹³

* Need to also assume R_{18} : will investigate how this works, given the CHaMP result that *R*18 varies… a lot! formed in Local Thermodynamic Equilibrium (LTE) at opacity in the CHaMP result that R_{18} varies... a lot!

> Work (with Prerak Garg) in an *l*=13° test map (1Q), but only over small areas (~few arcmin2)

Future Work

- * Connect *N*_{CO} catalogues from SCIMES (T:1-0, S:2-1) with properly segmented dust-based N_{H2} structures (CODEX project)
- * Map abundances [¹³CO]/[H₂] and $R_{13} =$ [¹²CO]/[¹³CO] across 4Q by combining N_{13} maps with dust-based N_{H_2} maps (still need to assume a single GDR)
- Re-analyse Galactic distribution of *N*H2 , *X*13, *T*ex, etc. with respect to spiral arms (globally) or filament/cloud structure & properties (locally)

Conclusions

- Main takeaway: *N*-based physics is different than *I*based physics, affecting inferences of mass, structure, excitation, other derived cloud properties. Ignoring this risks the validity of your science.
- These projects are staff-limited: postdocs, students, please help!