Physical Conditions and Star Formation in Cluster-Forming Molecular Clumps

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The Problem of Massive SF

- *Milky Way is ideal local calibrator for tracers of massive star/cluster formation seen in other galaxies and to high redshift, but...*
- *Systematic MW surveys of massive star formation/cluster formation difficult because of rarity => large distances, also short timescales, complex phenomenology*
- *Typically plagued with selection effects, small sample size, uniformity, limited fields of view*
- *Need uniform, wide sky coverage, high resolution, AND multiple wavelengths*
- *Started CHaMP in 2002: new results address these issues...*

What is CHaMP?

The Galactic

Census of High- and Medium-mass Protostars

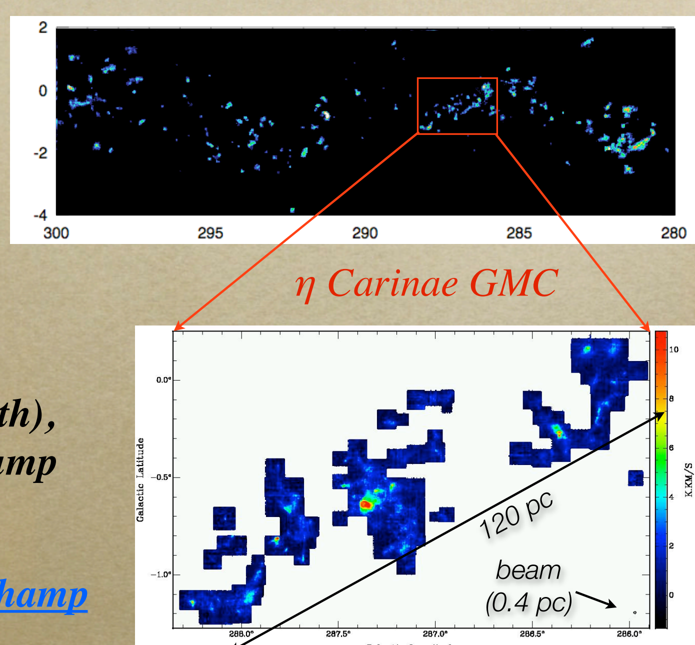
- *Based on Nanten maps (PIs Yonekura, Fukui)*
- *An unbiased multi-wavelength Galactic Plane survey (20°×6°) of a complete population (303) of massive, dense, parsec-scale molecular clumps*
- *At 3mm with Mopra (2004–2012): simultaneous maps of MANY molecular tracers*
- *In NIR+MIR (2007–2013) with AAT (Stuart Ryder), CTIO (Krista Romita), Warm Spitzer*

1. CHaMP in HCO^+

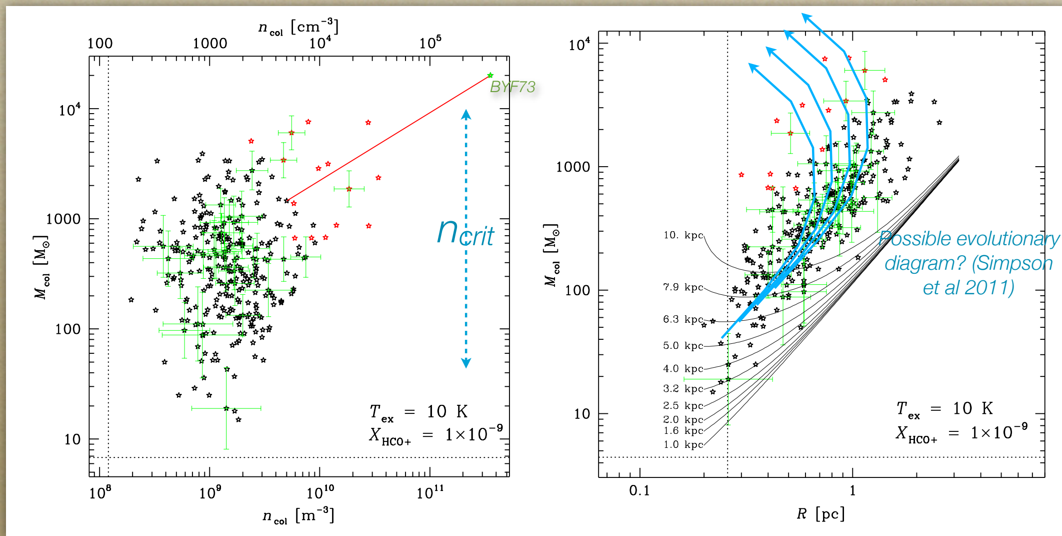
Barnes et al 2011 ApJS 196 12

ONLINE:
All data cubes, moment maps (integrated intensity, velocity field, linewidth), and data tables of clump properties:

www.astro.ufl.edu/champ



HCO^+ results



mass-density ***mass-radius***

HCO^+ summary

- ***Vast population of massive (10–10⁴ M$_\odot$), dense (3×10$^{2–4}$ cm^{-3}), pressure-bounded, but subthermally-excited clumps — predicted by Narayanan et al 2008. Consistent with emerging view of KS laws being physically based on amount of dense gas present, not just all gas***
- ***Most of these seem (relatively) quiescent in their massive SF activity***
- ***Implies a long, quiescent lifetime for clumps (50 – 100 Myr) before massive SF turns on***
- ***Can reconcile "short-" and "long-lived" views of massive star-forming clumps***

2. CHaMP in IR

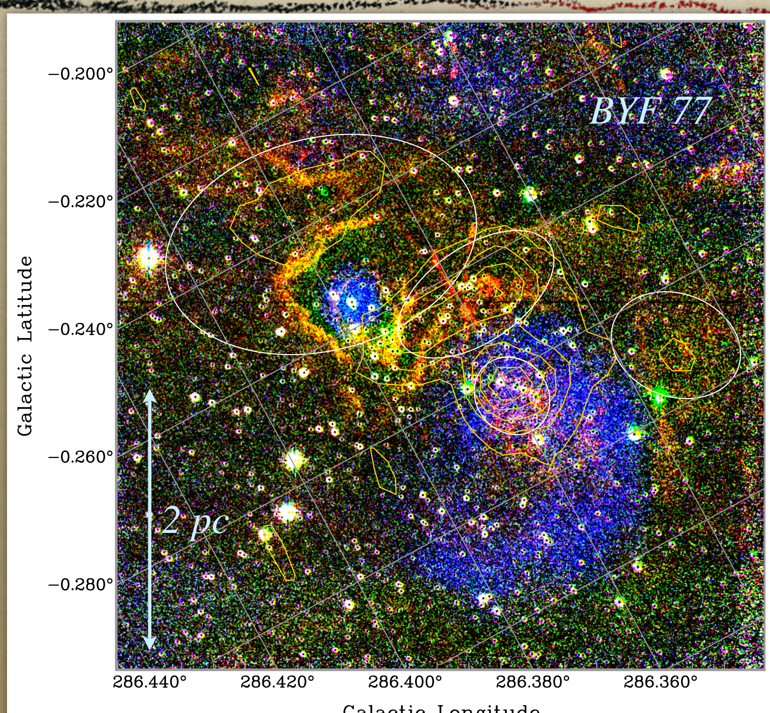
- *AAT+CTIO broadband JHK imaging & photometry*
- *Deep Warm Spitzer IRAC Band 1+2 mosaics of 90% of HCO^+ clumps: imaging & photometry*
- *GLIMPSE Band 3+4 photometry*

} *Large-scale near- & mid-IR embedded cluster demographics, in prep.*

- *Narrowband NIR results for 20% of clumps (Barnes et al 2013 MNRAS 432 2231) :*
  - *line-free K-continuum*
  - *H_2 v=1–0 S(1)*
  - *H_2 v=2–1 S(1)*
  - *Brackett-γ*

} *Use line-free K-cont to make continuum-subtracted line images*

Compare mm and NIR-narrowband

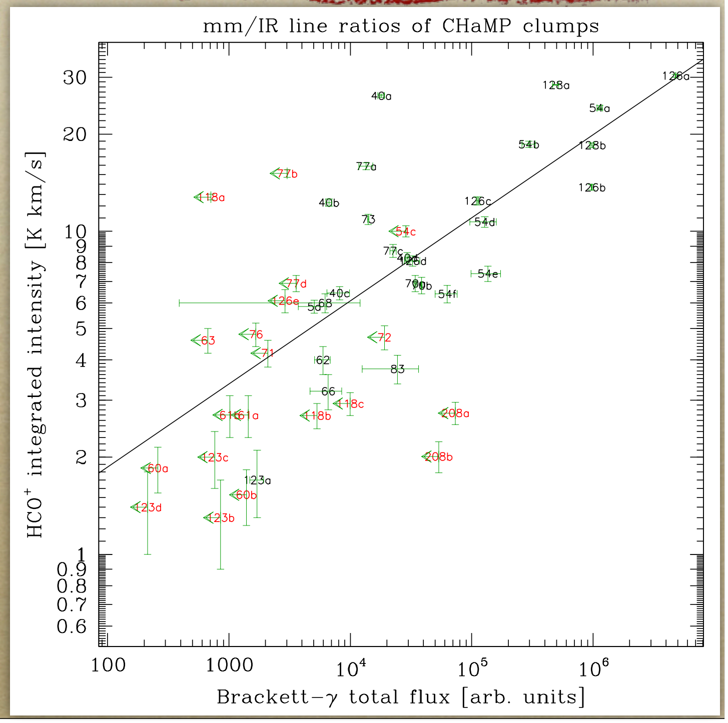


AAT images:
H_2 v=1–0 S(1)
H_2 v=2–1 S(1)
Brγ

Mopra contours:
N_2H^+

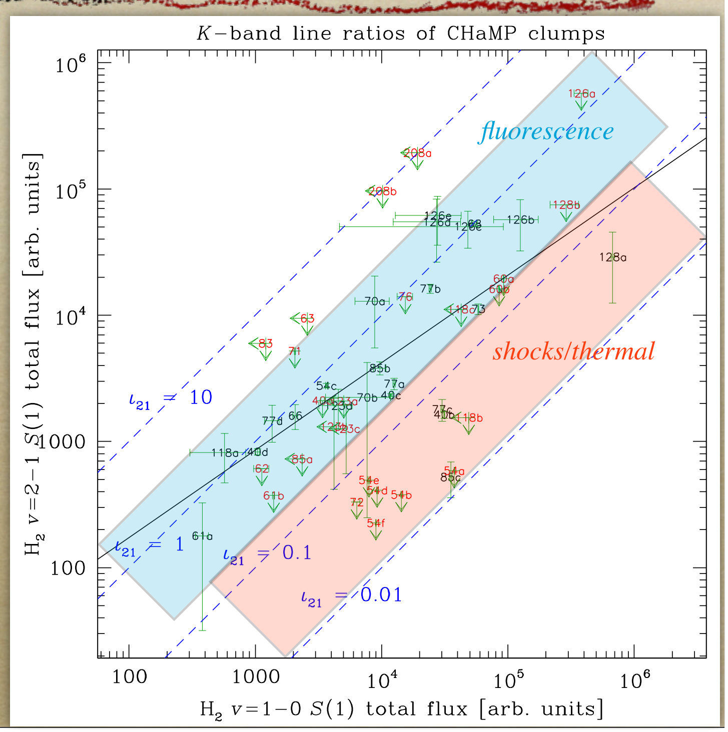
New signposts

- ***HCO⁺ (brightness, not linewidth!) and Brγ are signposting the same thing: how can this be?***
- ***N_2H^+ and H_2 lines are NOT correlated with each other, nor with HCO⁺ or Brγ***



New signposts

- ***However, H_2 line emission is dominated by fluorescence, not shocks***
- ***Consistent with observed morphology (mostly around HII regions, not many outflows)***

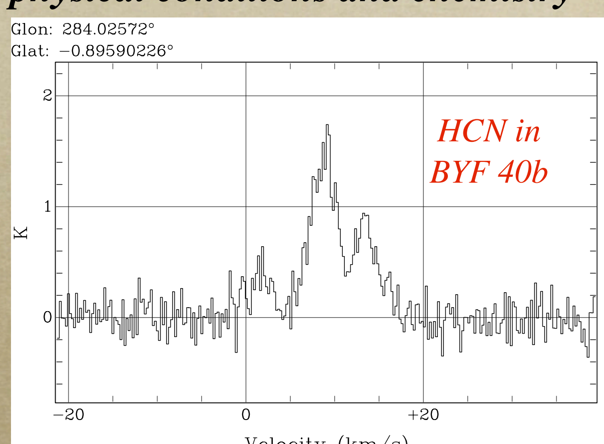


NIR-narrowband summary

- *HCO^+/N_2H^+ ratio seems correlated with ionising flux from a clump's embedded MYSO population (cf Meyer & Turner 2012 results for Maffei 2)*
- *HCO^+, Brγ, and H_2 seem to signify a late-stage surge in massive star/cluster formation and photon-driven evolution*
- *Supports picture of long-lived clumps terminated by MSF*
- *N_2H^+ seems a better tracer of pre-cluster cold gas*
- *"Dense gas" tracers do not trace a homogeneous population of clouds!!!*

3. Hyperfine CHaMP

- *Maps of hyperfine-split lines of HCN and N_2H^+ can produce spatially-resolved maps of physical conditions and chemistry*
- *Analysis of hyperfine physics can be compared in detail with HCO^+ and other species' simple J-line abundances and kinematics*
- *Tools of choice: pyspeckit + Miriad + shellscript*



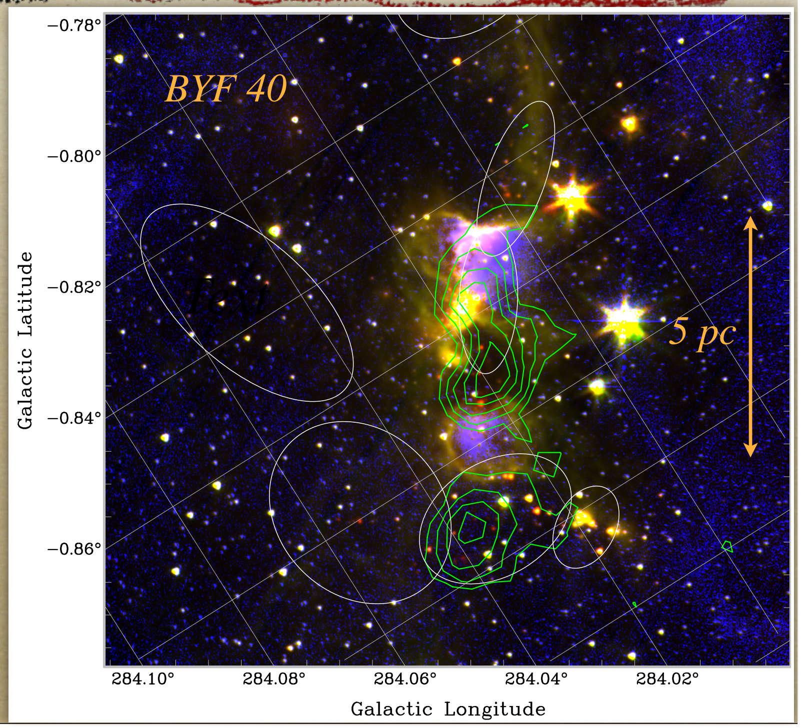
- *Start with HCN in one region of 7 clumps:*
  BYF 40 d ~ 6.6 kpc M ~ 2000–7000 $M_\odot$/clump

NIR + MIR + 3mm

images:
DWS: band 2
DWS: band 1
AAT: Brγ

contours:
N_2H^+

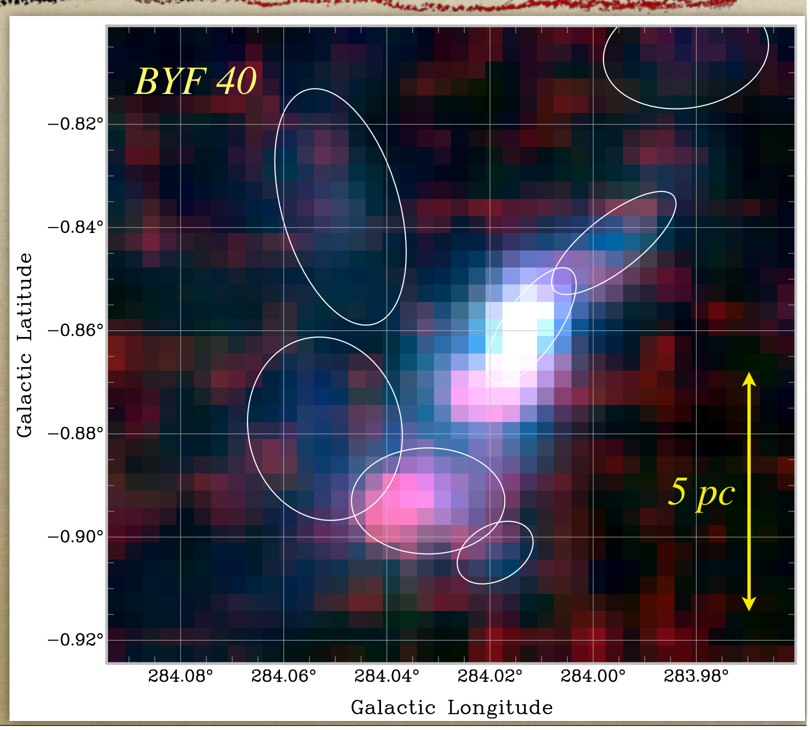
ellipses:
HCO^+ clumps'
HPW



NIR + MIR + 3mm

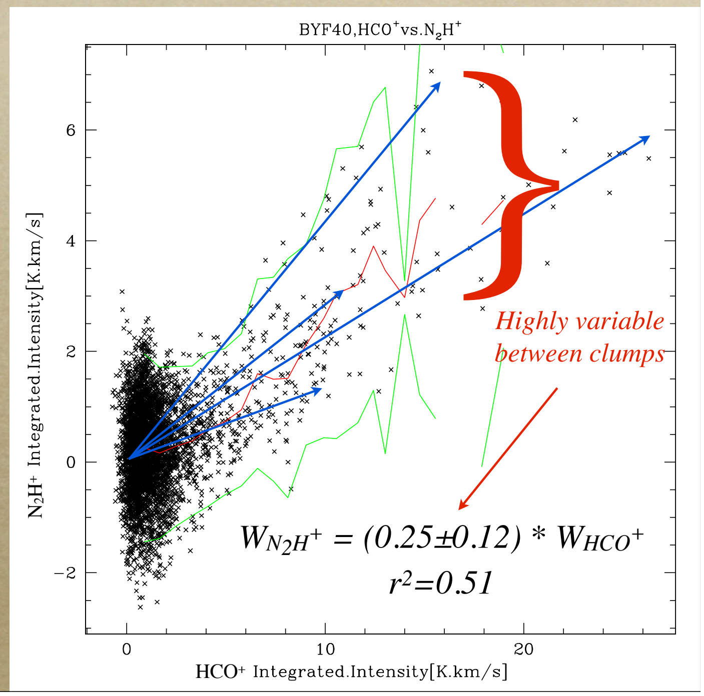
images:
N_2H^+
HCN
HCO^+

ellipses:
HCO^+ clumps'
HPW



"Dense gas" tracers

- ***CHaMP clumps show similar 3mm morphology & distribution among many molecular tracers, e.g. HCO^+, HCN, ^{13}CO***
- ***N_2H^+ is very different to these (probably due to CO freeze-out and desorption, producing and destroying N_2H^+)***

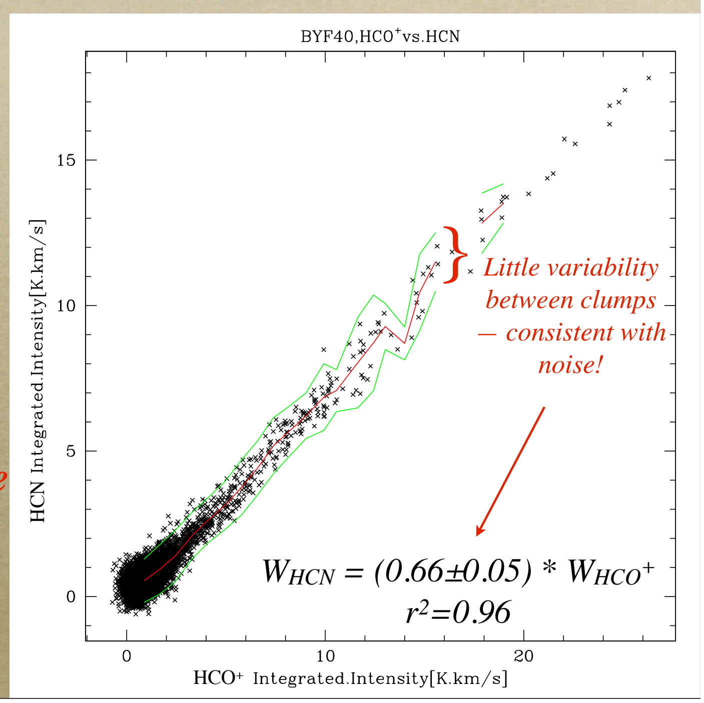


"Dense gas" tracers

- ***So N_2H^+ line flux is temperature and/or ionisation-sensitive***

BUT!

- ***HCN and HCO^+ (at least) must share very similar chemistry!***
- ***So this ratio is temperature-INsensitive***
- ***But from Brγ, HCO^+ and HCN line flux are ionisation-sensitive***



$5{\times}10^4$

What about column densities?

- ***Simple radiative transfer analysis:***

$$N_{HCN} = 9.0{\times}10^{15}\mathrm{m}^{-2}\ \frac{Q(T_{ex})\ e^{E_{up}/kT_{ex}}}{1-e^{-h\nu/kT_{ex}}}\int\tau\ dV_{km/s}$$

- ***Normally** use $J_b = (J_{ex}-J_{bkgd})(1-e^{-\tau})$ and $\tau << 1$ to estimate $\tau \sim J_b/J_{ex} \sim T_b/T_{ex}$, and obtain N from $W = \int T_b\, dV$ and T_{ex} from other methods (sometimes assumed)*

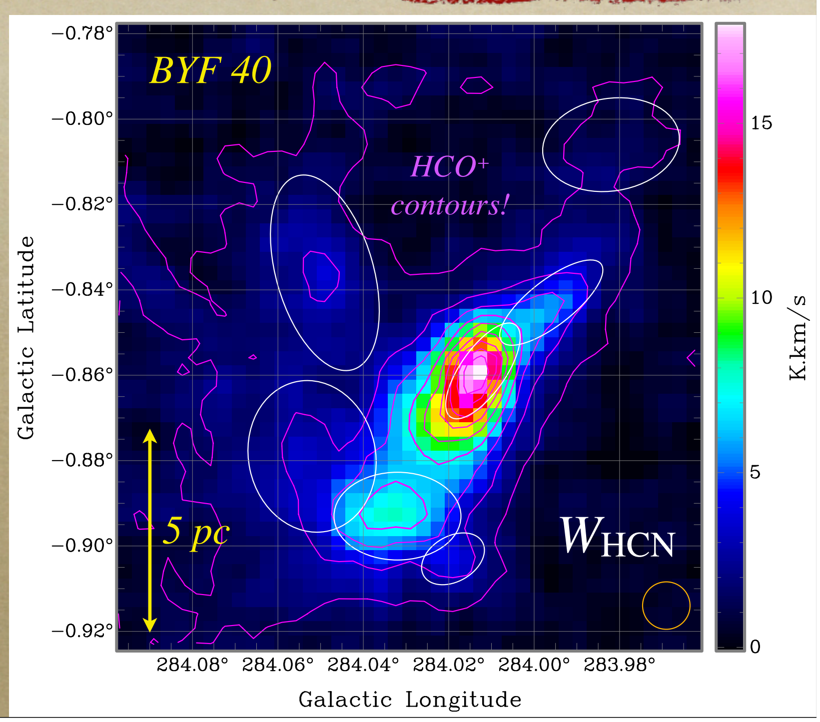
- ***Hyperfine-split lines** give τ and T_{ex} **directly** (also V_0, σ_V) assuming only that HF ratios are in LTE: gives N without further assumptions or cross-calibration uncertainties*

- ***Then get mass from abundance, or vice versa***

H_0

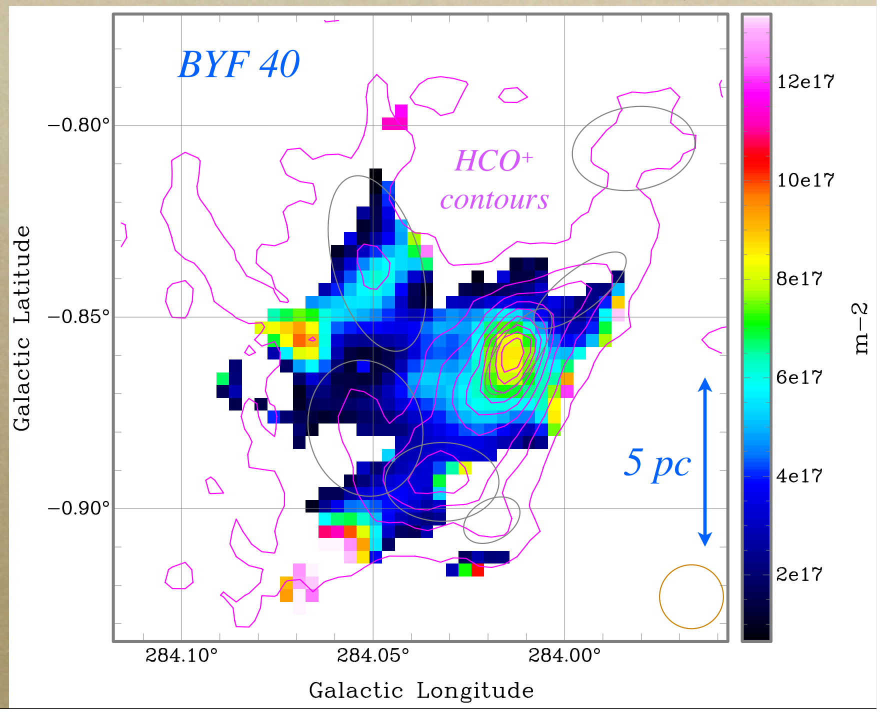
Start with HCN data cube

Use pyspeckit/ Miriad/ shellscript to convert full hyperfine spectrum to N_{HCN}, pixel by pixel



Map of N_{HCN}

This looks different! "Flatter" than W_{HCN}

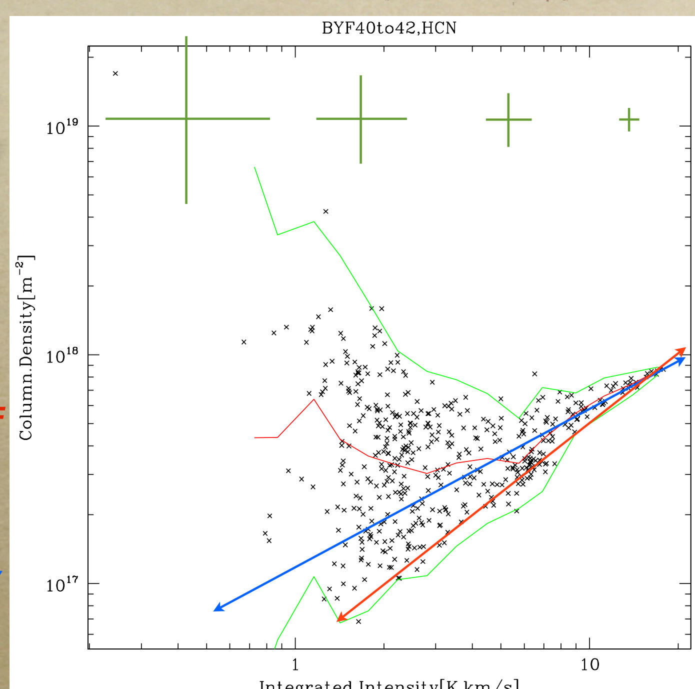


HCN hyperfine results

- *Something unexpected is happening at low W!*

Normal method when we don't know τ, T_{ex}: use W_{HCN} to estimate N_{HCN}

- *Linear relation: $N_{HCN} = (5\times10^{16}m^{-2}) * W_{K.km/s}$*
- *Power law: $N_{HCN} = (1.2\times10^{17}m^{-2}) * W_{K.km/s}^{0.7}$*



HCN hyperfine results

- *Convert to mass column assuming $X_{HCN} = 10^{-9}$ (same as X_{HCO^+}): $\Sigma(M) = 24{,}000$ or $37{,}000\ M_\odot$*
- *BUT we can measure N_{HCN} in each pixel without assuming a conversion from W, and sum these to get a total (mass) column: actual $M_{tot} = 57{,}000\ M_\odot$!*
- *This is ~2× naïve "W methods" because of large areas with low W, low T_{ex}, high τ, and yet high N. (Note that this is an overall result: some clumps are much more massive, some actually less, than with W methods.)*
- *cf. mass of these clumps as measured by $HCO^+ \sim 16{,}000\ M_\odot$ But masses must be the same => $X_{HCN} \sim 4 {*} X_{HCO^+}$*

Applications & Implications

- *Can use this information to obtain self-consistent relative abundance maps between HCO^+ and HCN (and other species): strong constraints on chemical models*
- *But more significantly....*
- *Mass estimates that rely on simple W scalings may substantially underestimate the gas mass in these clumps!*
- *Implies there is a lot more "dense" gas in massive clumps not engaged in massive star formation: extends HCO^+ results*
- *Consequences for clump stability, calibration of K-S relations, among many other things....*

Next steps

- ***Need to apply these methods to HCN maps of the rest of the 303 CHaMP clumps***
- ***Derive T_{ex} and relative abundance maps; new mass estimates?***
- ***Relate to NIR+MIR data***
- ***Make results publicly available for modellers on CHaMP web pages: FITS files of data, derived quantities; machine-readable tables+catalogues***
- ***Extend analysis to N_2H^+ data, other species***

Thank you