Models of cold massive cores

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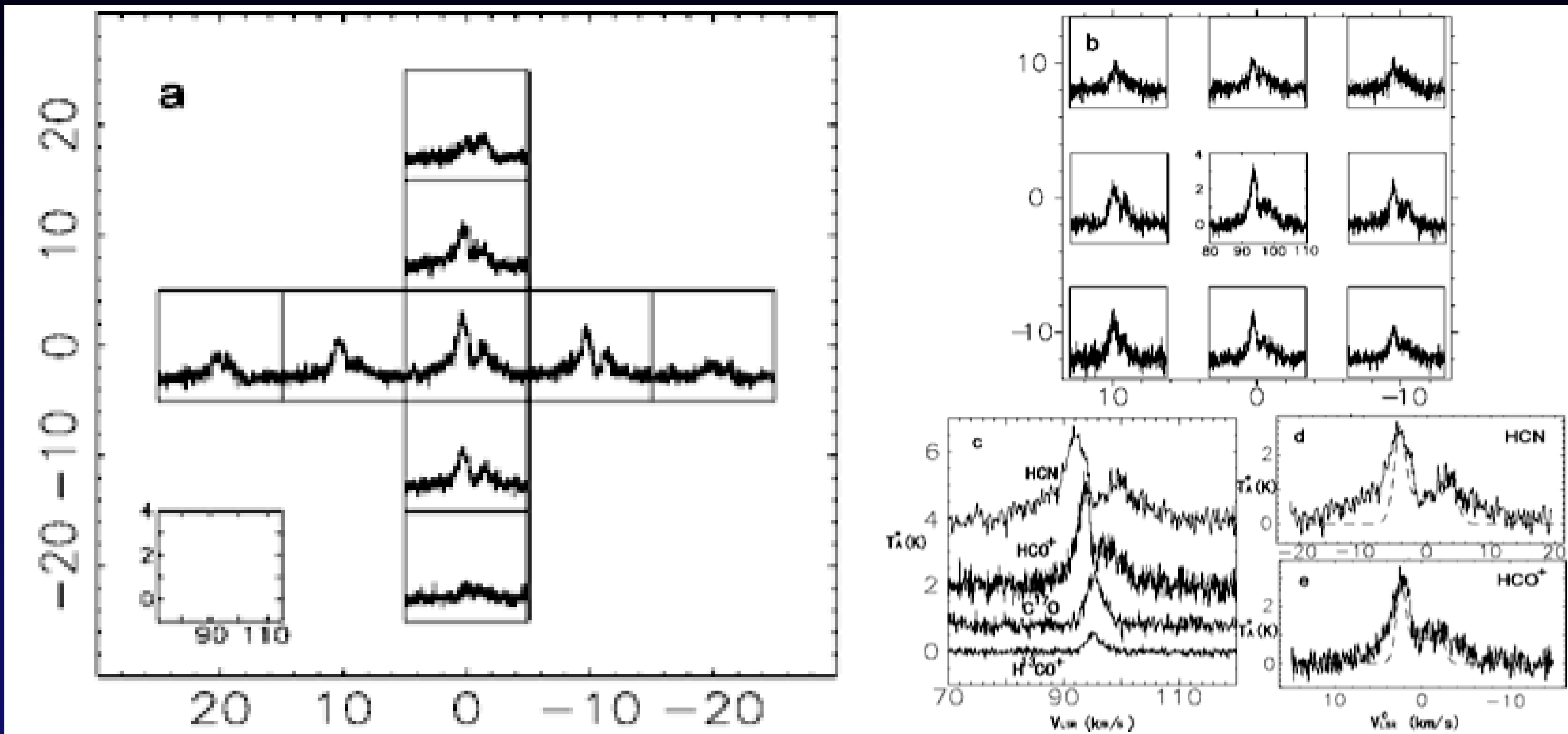
High mass star formation

How does high mass star formation diverge from being a scaled up version of low mass star formation?

Need to identify the equivalent of the starless cores for low mass star formation

Some recent discoveries of just such objects - cold massive cores - have been made

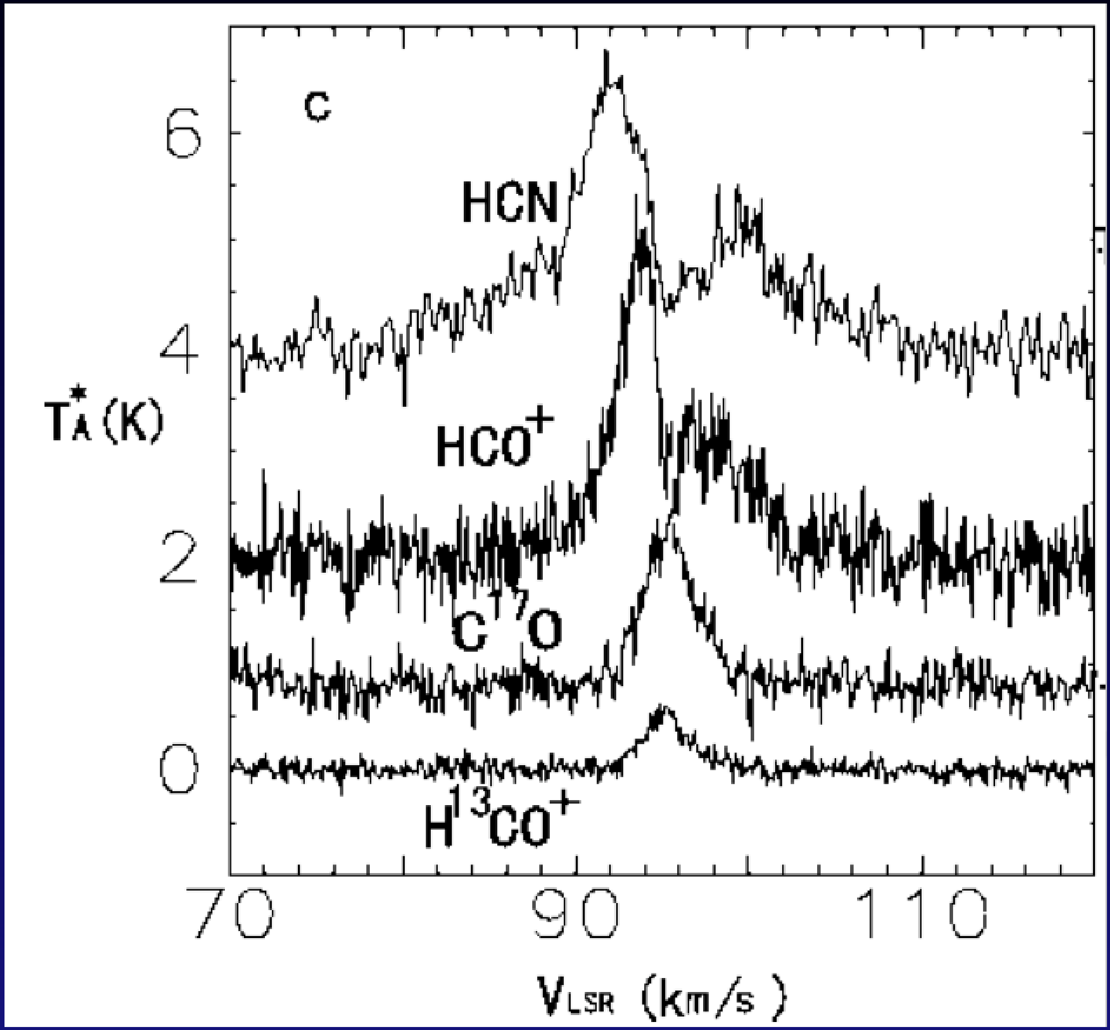
High mass star formation



JCMT 18354-0649S Wu et al 2005, ApJ 628, L57

Another source is ISOSS J18364-0221 Birkman et al, ApJ 637, 380

Collapse motions seen?



Line profiles look similar to low mass counterparts - are the same processes at work?

Modelling

Radiative transfer modelling is carried out with a 3D molecular line transport code written originally by Eric Keto

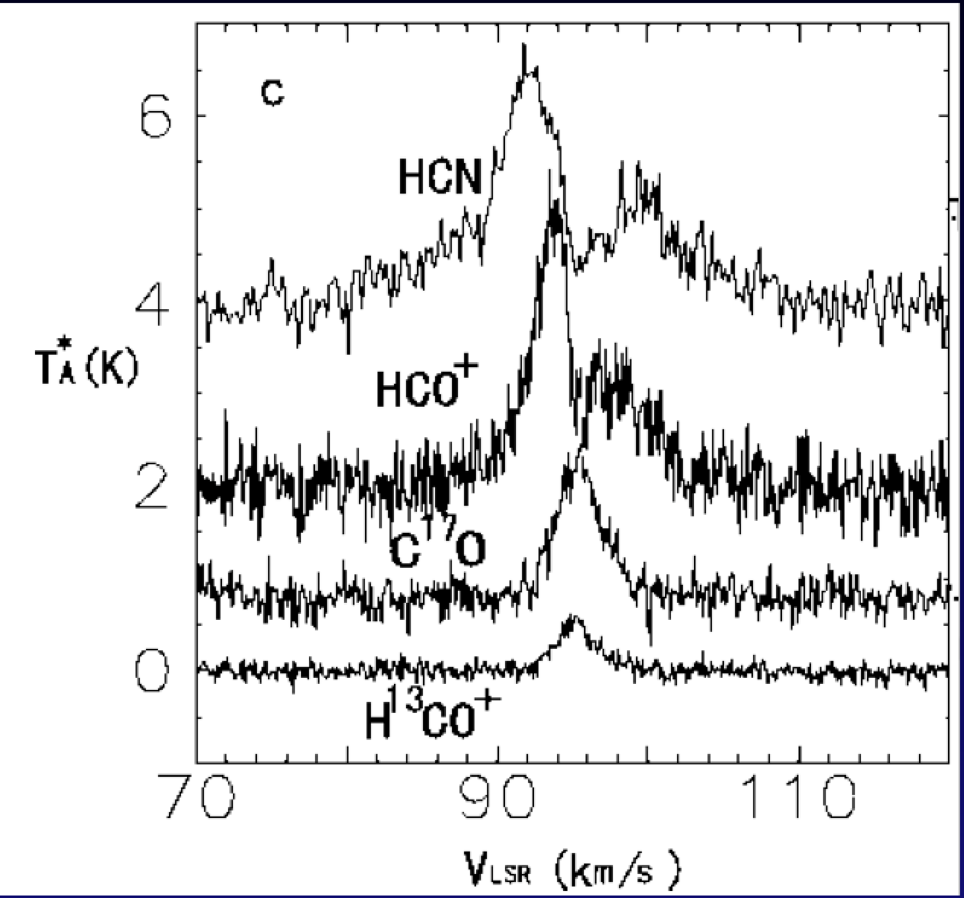
Each cell in the 3D grid is given a temperature, turbulent width, velocity, density and chemical abundance

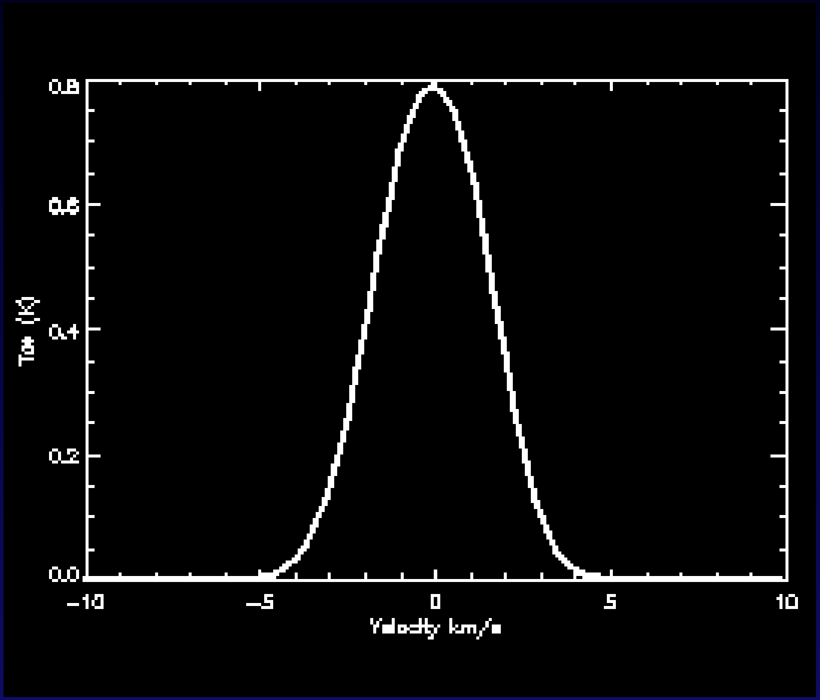
The code calculates level populations and hence emission seen by an observer

Can load observations into the code and run multiple models

Keto et al, 2004, ApJ, 613, 355
Rawlings et al, 2004, MNRAS,351, 1054
Redman et al, 2004, MNRAS, 352, 1365

H^{13}CO+ (3-2)

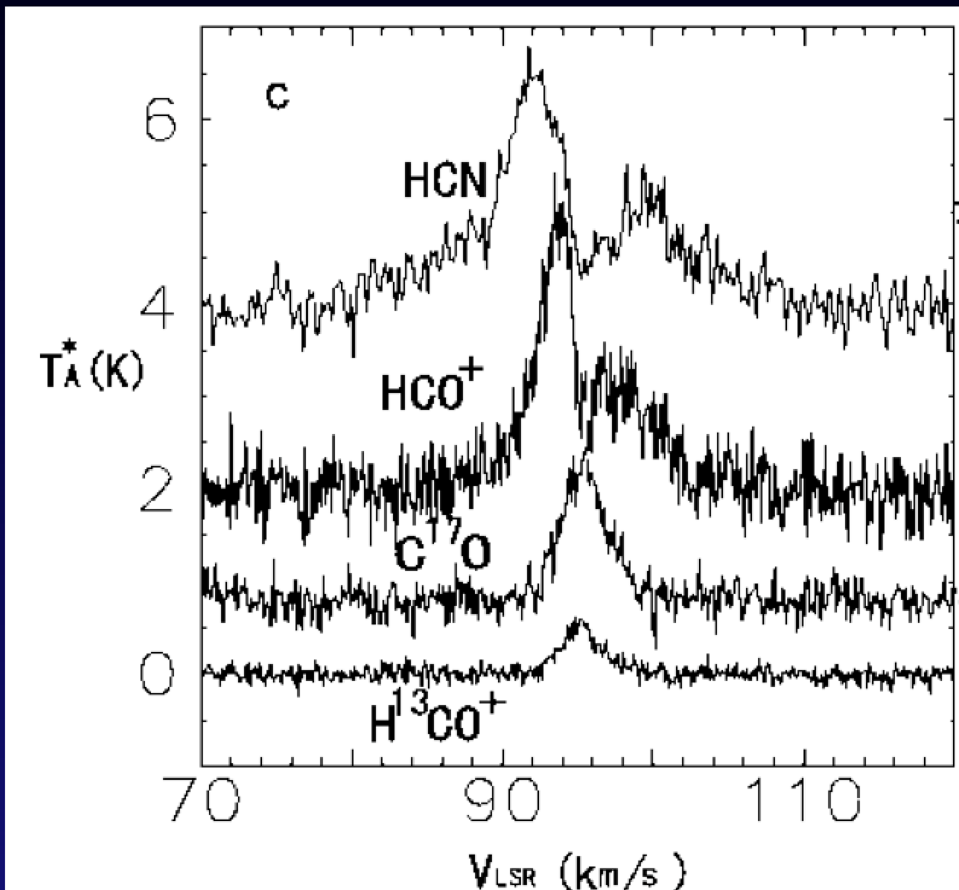


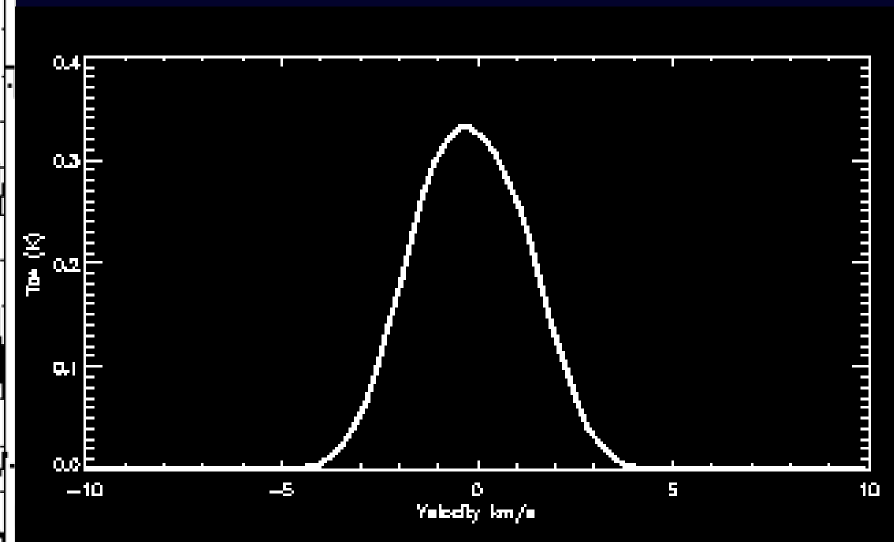


H^{13}CO+

Low abundance, optically thin, constrains turbulent width

$C^{17}O$ (2-1)

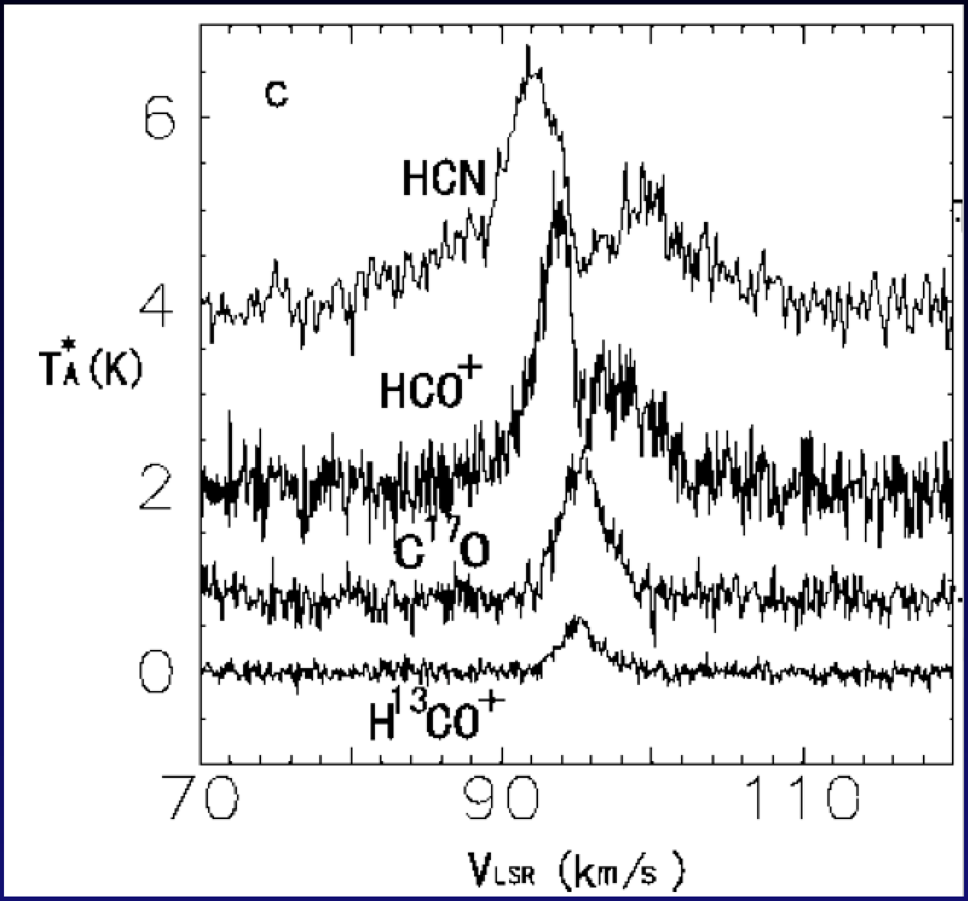


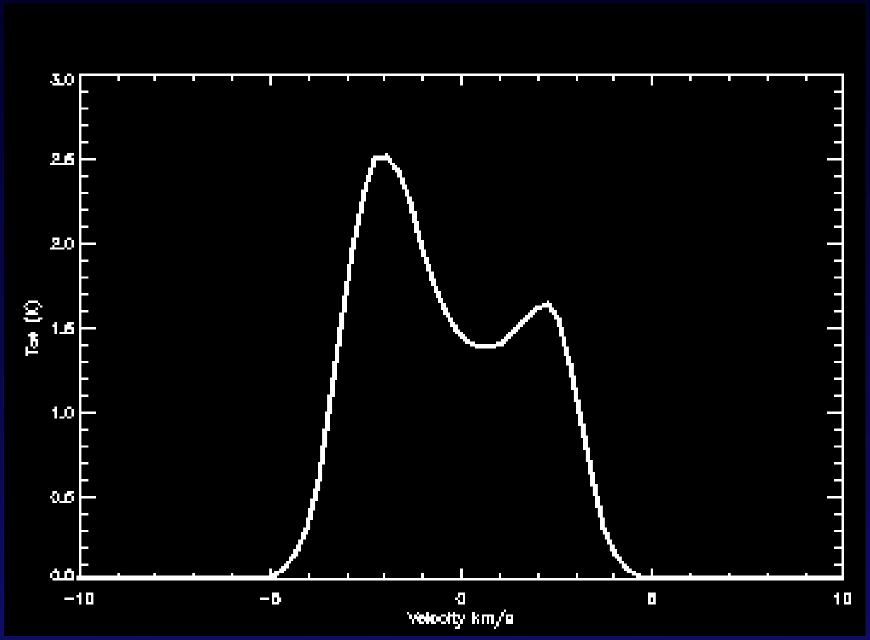


$C^{17}O$

Also optically thin. Constrains depletion due to freeze-out

HCO$^+$ (3-2)

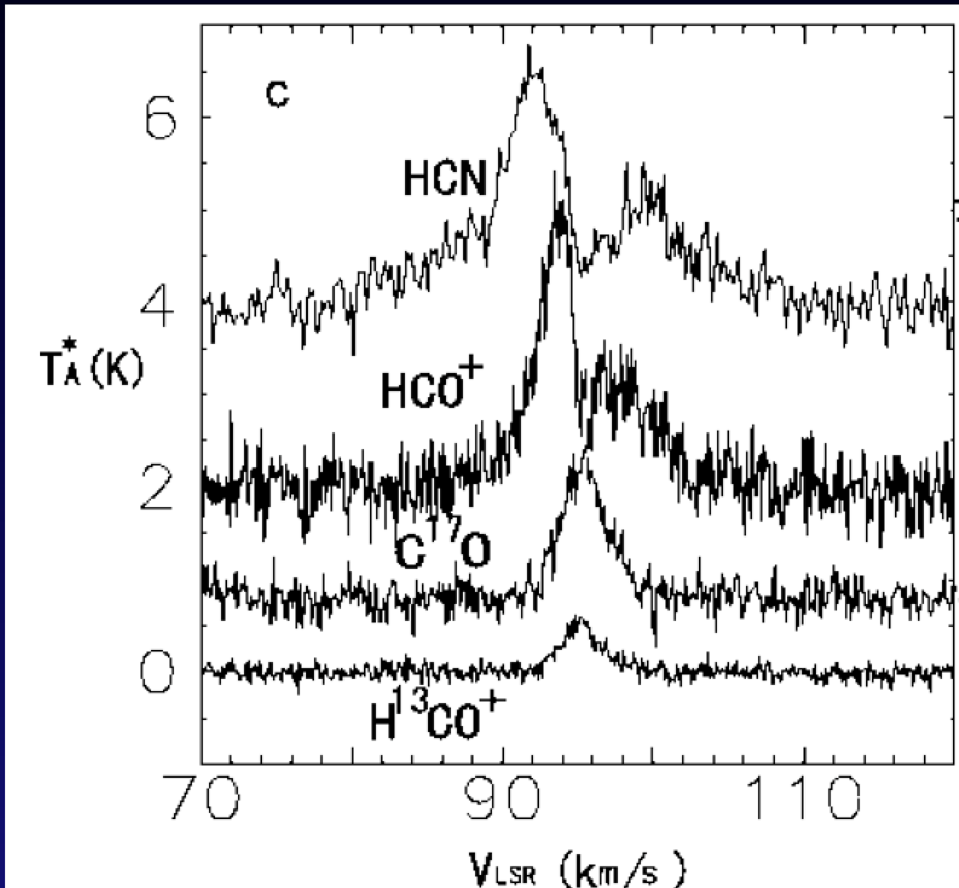


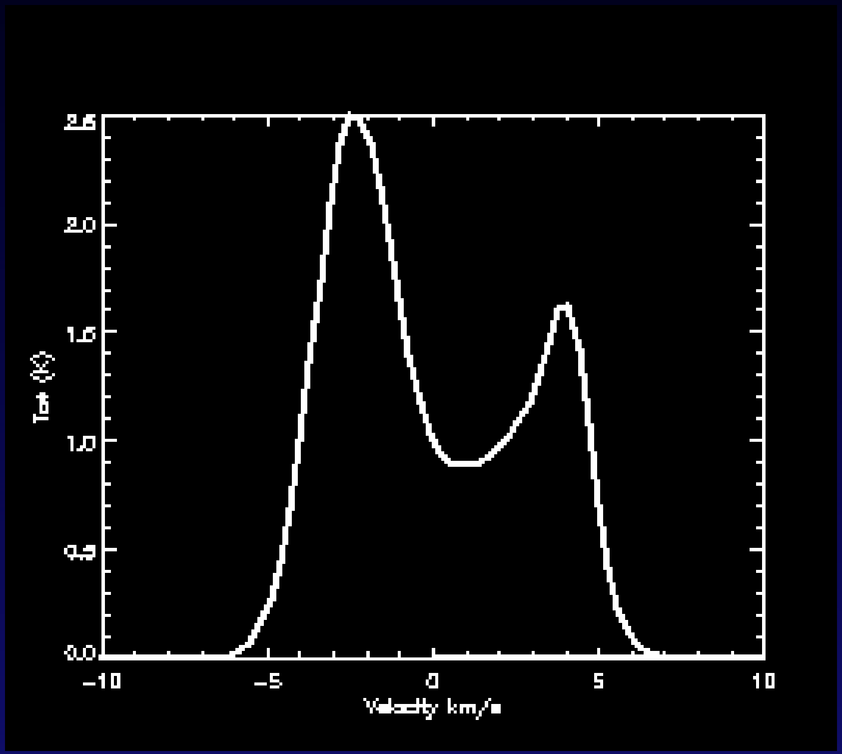


HCO$^+$

Self-absorbed so constrains infall. Also gives 12C/13C ratio.

HCN (3-2)

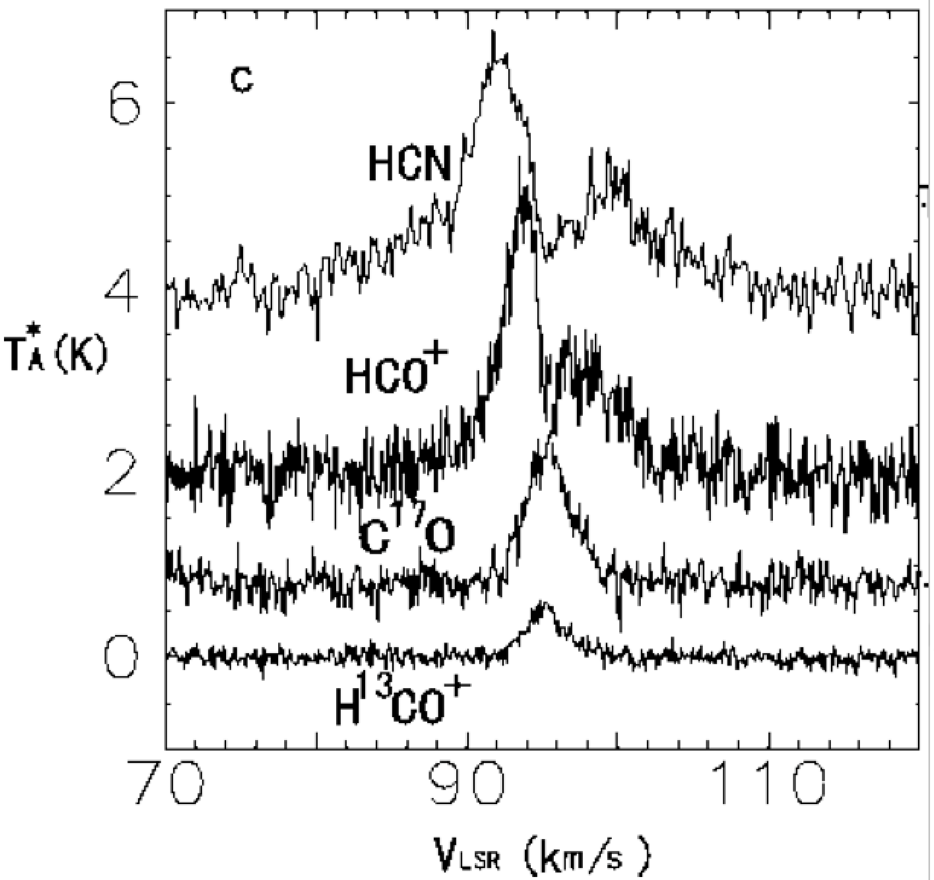


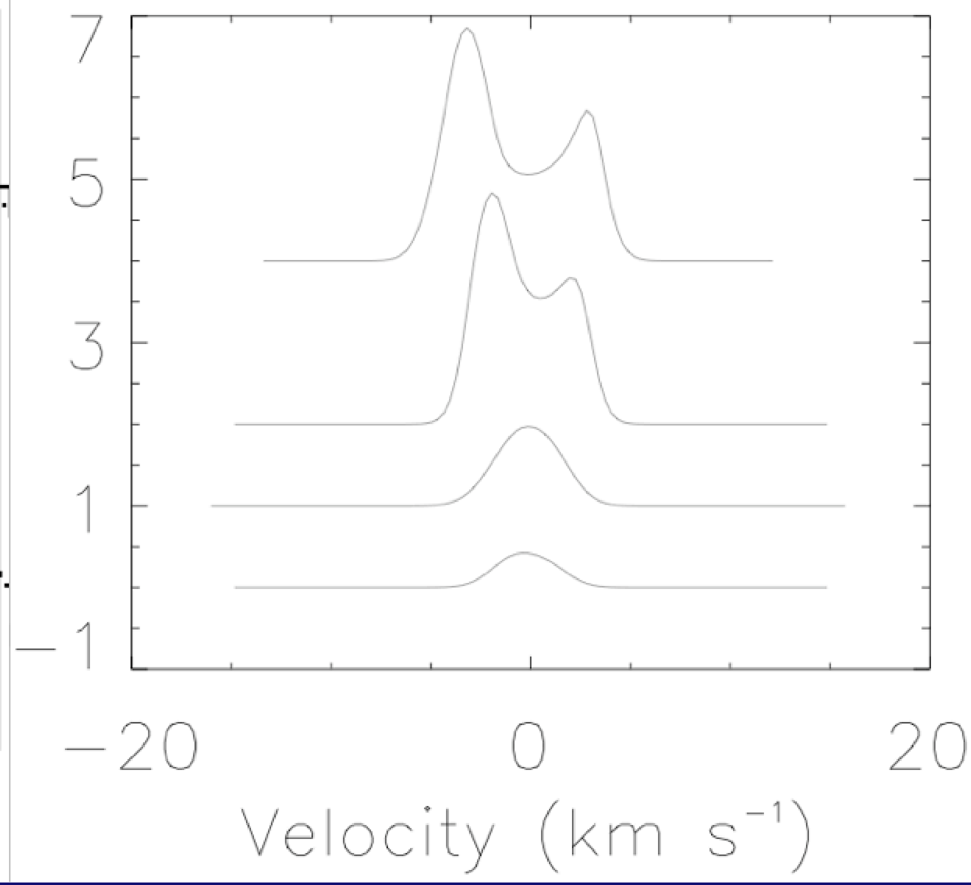


HCN (3-2)

Infall seems displayed even better than in HCO+

Collapse motions modelled





The line shapes, widths and strengths can all be reproduced. Depletion of all molecules and infall needed

HCN as an infall tracer?

HCN appears to be a better infall tracer than HCO^+

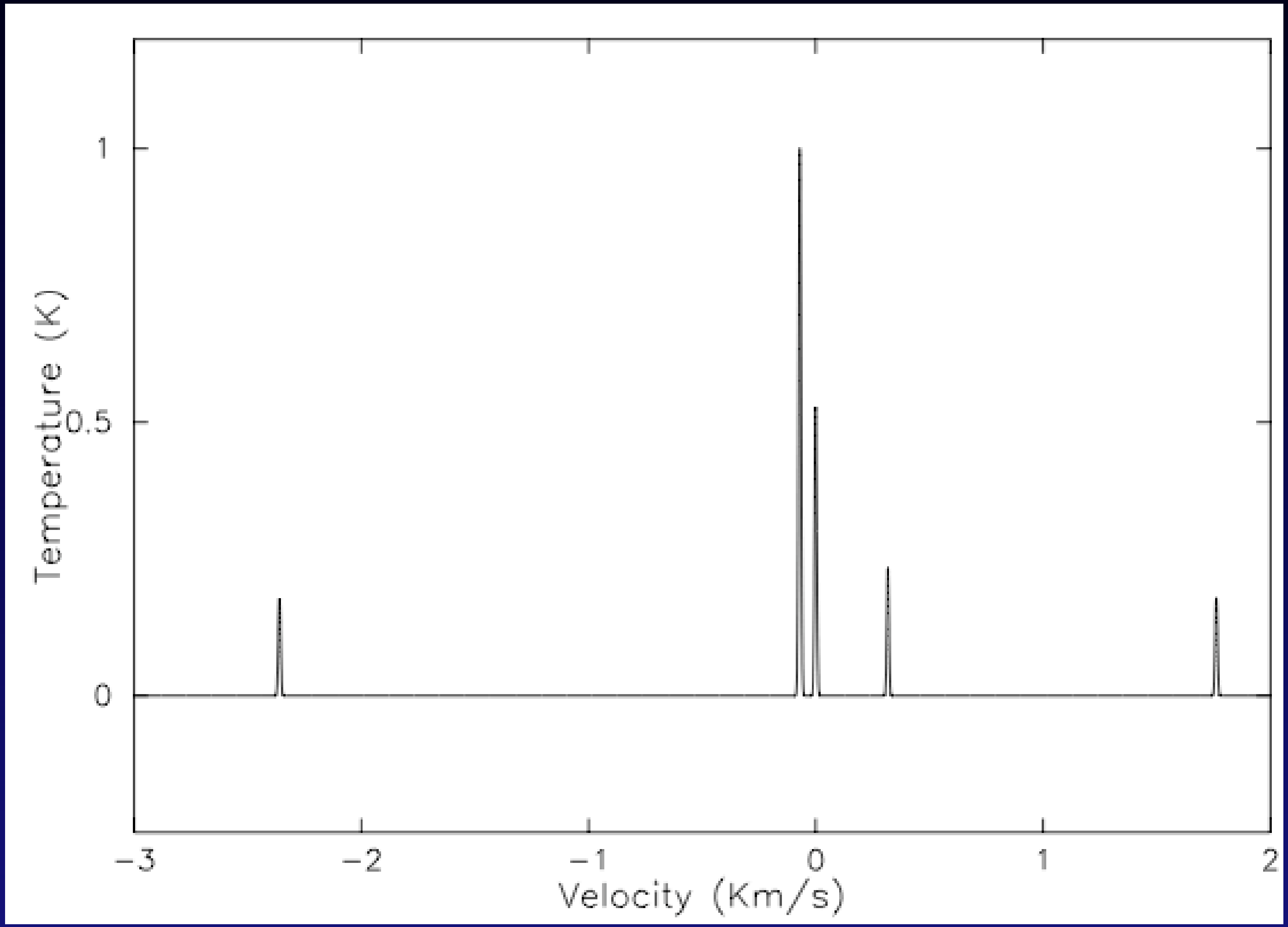
Seems more resistant to freeze-out and is a high density gas probe - less prone to surface effects

Asymmetries seem more clearly displayed

Why not use HCN instead?

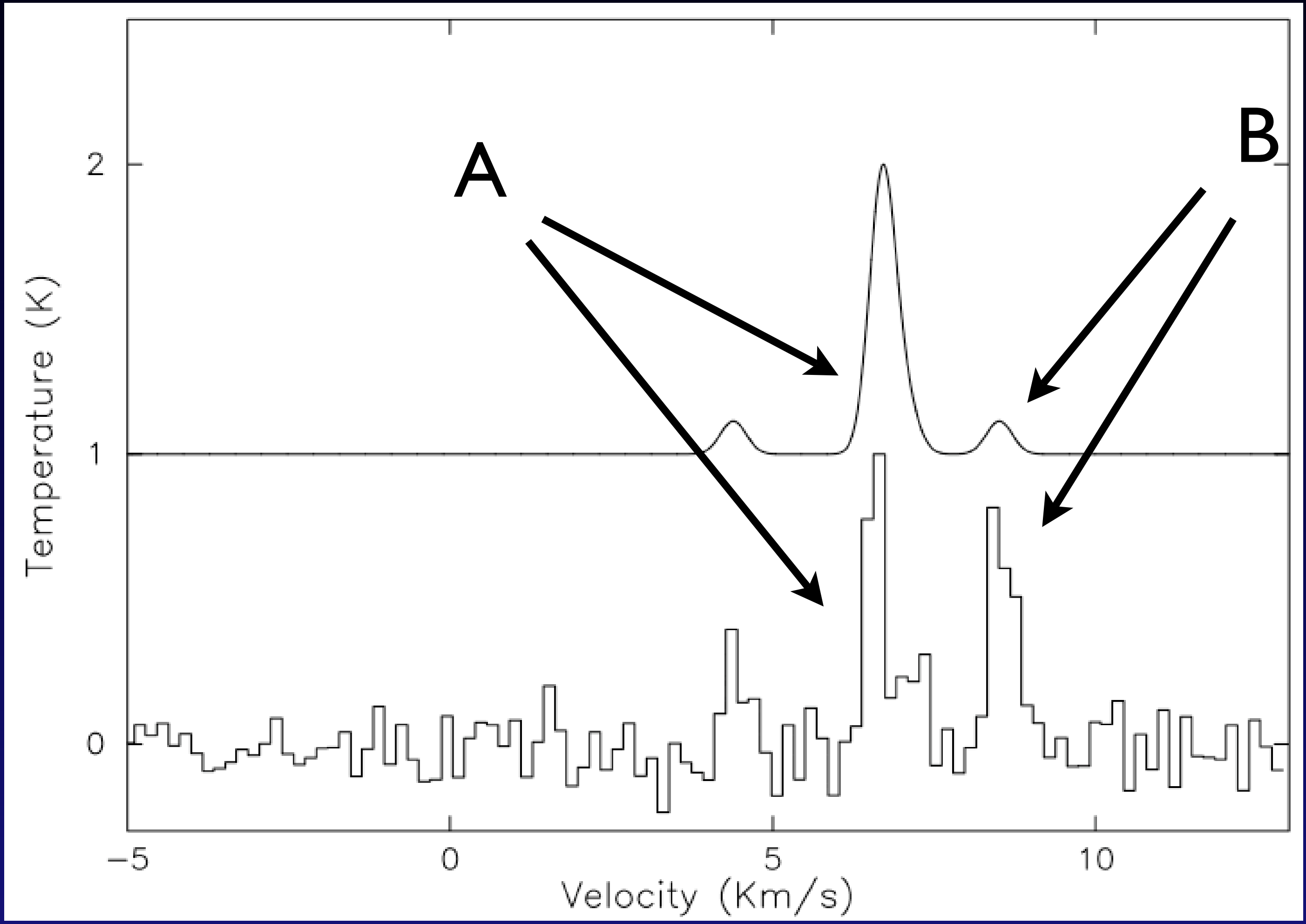
Hyperfine lines in HCN

HCN
J=3-2



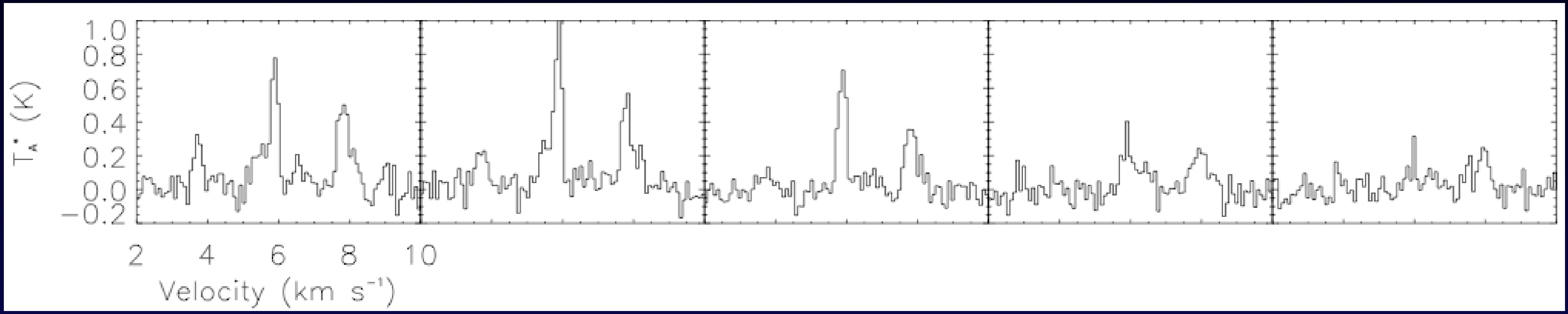
HCN has a hyperfine line structure

Hyperfine lines in HCN



HCN has hyperfine anomolies

Hyperfine lines in HCN



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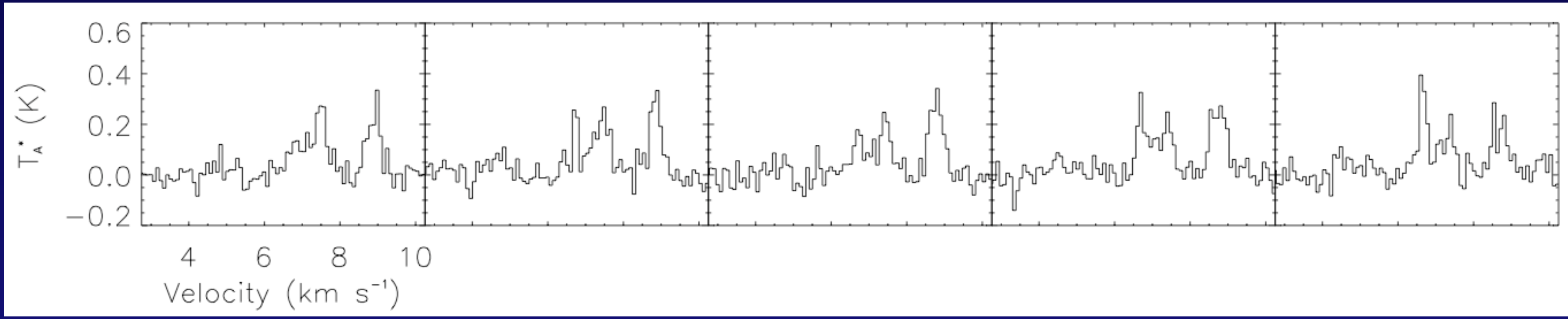


L1521F

The anomolies are common: what is going on?

Hyperfine lines in HCN

At the low J levels, the hyperfine components are well separated

Higher J levels they are blended

Some kind of line overlap is taking place - pumps some of the lower transitions

Hyperfine lines in HCN

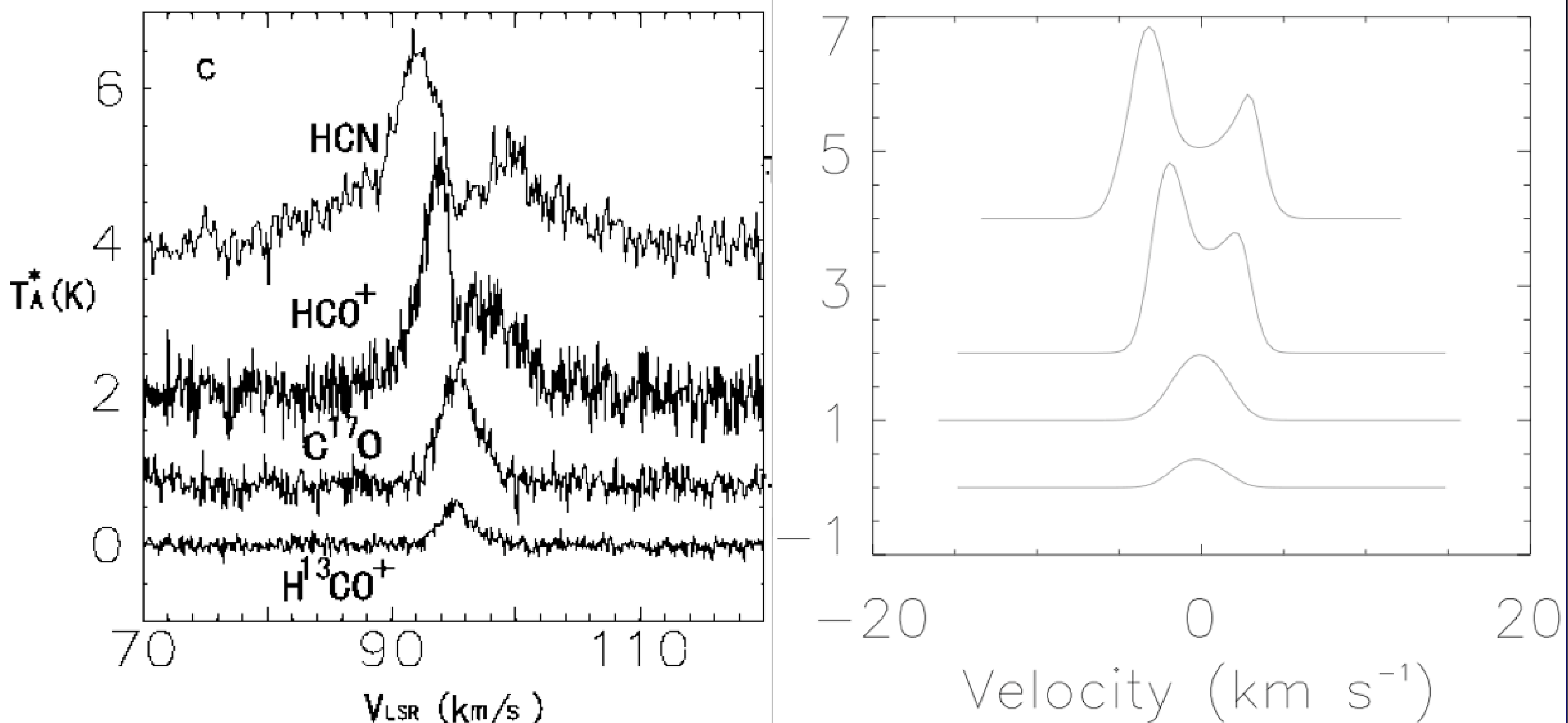
Model by dividing the known collisional rates among the J levels between the hyperfine lines according to their statistical weights

Aim to fence off the parameter space where the anomolies appear (Loughnane et al, in prep)

Not known if anomolies present in cold massive cores too but hyperfine structure will distort line shape

Meanwhile, HCN should be used cautiously as an infall tracer

Collapse motions modelled



The line shapes, widths and strengths can all be reproduced. Depletion of all molecules and infall needed

Cores compared

High mass core

T range 10-15 K
Central density 10^6 cm^{-3}
X(HCN) 1×10^{-9}
X(HCO^+) 2×10^{-10}
X($C^{17}O$) 2×10^{-9}
X($H^{13}CO^+$) 2×10^{-11}
Depletion radius r/R ~ 0.5

Radius ~ 0.3pc
Infall velocity 1 km s^{-1}
Turbulent velocity 1.5 km s^{-1}

Cores compared

Cold massive core

T range 10-15 K
Central density 10^6 cm^{-3}
X(HCN) 1 x 10^{-9}
X(HCO^+) 2 x 10^{-10}
X($C^{17}O$) 2 x 10^{-9}
X($H^{13}CO^+$) 2 x 10^{-11}
Depletion radius r/R ~ 0.5

Radius ~ 0.3pc
Infall velocity 1 km s^{-1}
Turbulent velocity 1.5 km s^{-1}

L483 low mass core (Carolan et al 2007)

T range 12 K
Central density 3 x10^5 cm^{-3}
X(C17O) 1 x 10^{-9}
Depletion radius r/R ~0.3

Radius ~ 0.08pc
Infall velocity 0.1 km s^{-1}
Turbulent velocity 0.15 km s^{-1}

Cold supersonic turbulence

Infall velocity 1 km s^{-1} and turbulent velocity 1.5 km s^{-1} are much greater than in low mass cores

Both much greater than isothermal sound speed

Supersonic turbulence dominates over thermal pressure. Origin of turbulence could be magnetic

Collisions of gas streams and turbulent eddies will lead to localised dissipation of energy and formation of dense clumps

In low mass star formation, stable starless cores are observed

Mass loaded accretion flows

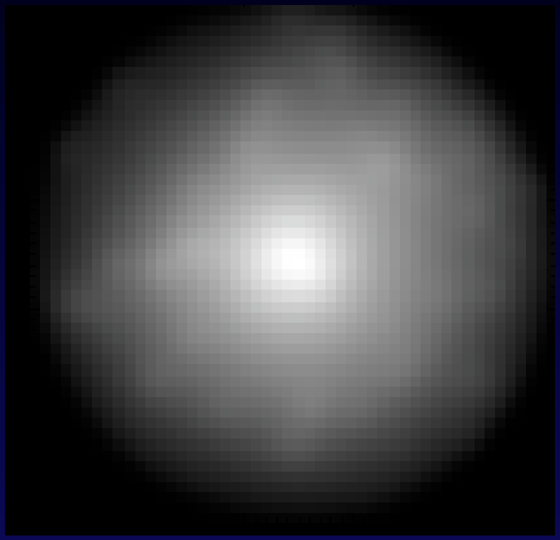
Model the accretion as being composed of discrete clumps

Later, the star can ionize the material between the clumps while heavy accretion continues

The radiation pressure cannot prevent a clump joining the accretion disk or accreting directly onto the star

High mass stars can be assembled without radiation pressure problems

Extent of the ionization is limited - leads to a hypercompact HII region



CO (4-3) model

Conclusions

Observations are begining to reveal the objects that will turn into massive stars

These objects seem to be scaled up versions of low mass starless cores with much larger turbulent widths, possibly due to a population of clumps

Clumps can (and should) be incorporated into models of cold massive cores, hot cores, hypercompact and ultracompact HII regions

Model ingredients

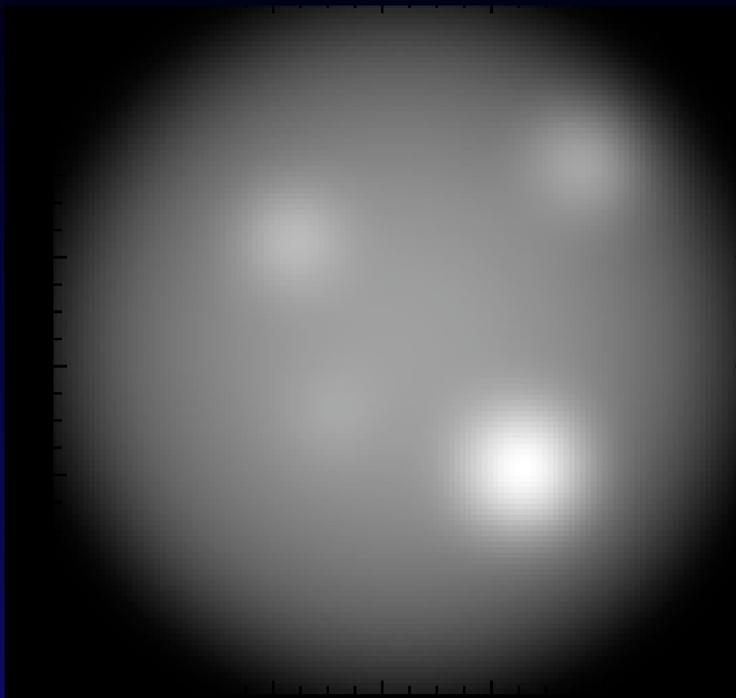
Dynamics of the mass-loaded accretion flow

Molecular line tracers (CO, HCO+, CS etc) used to trace collapse - infall signatures already seen but outflow and rotation will be present too

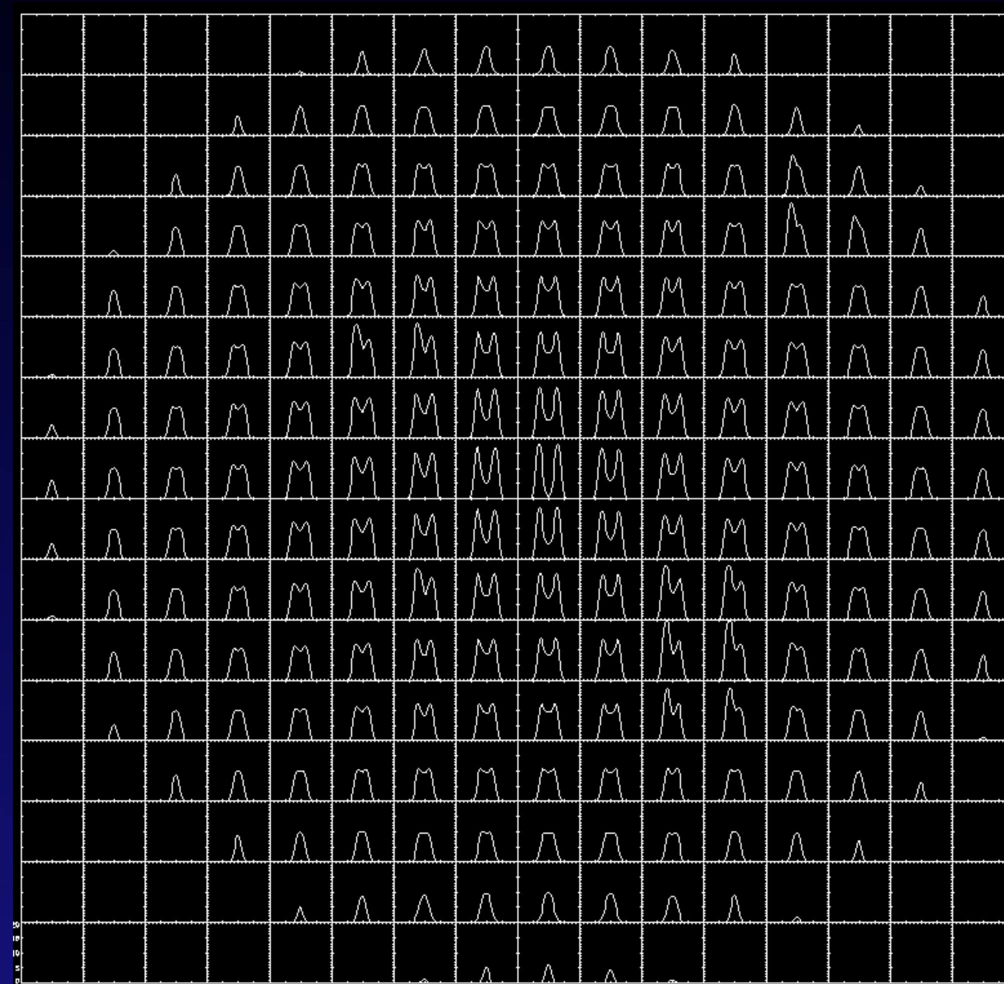
Chemistry of hot molecular core complex but required to give abundances of the tracers in the system

3D molecular line radiative transfer code to make predicted emission maps

Model ingredients

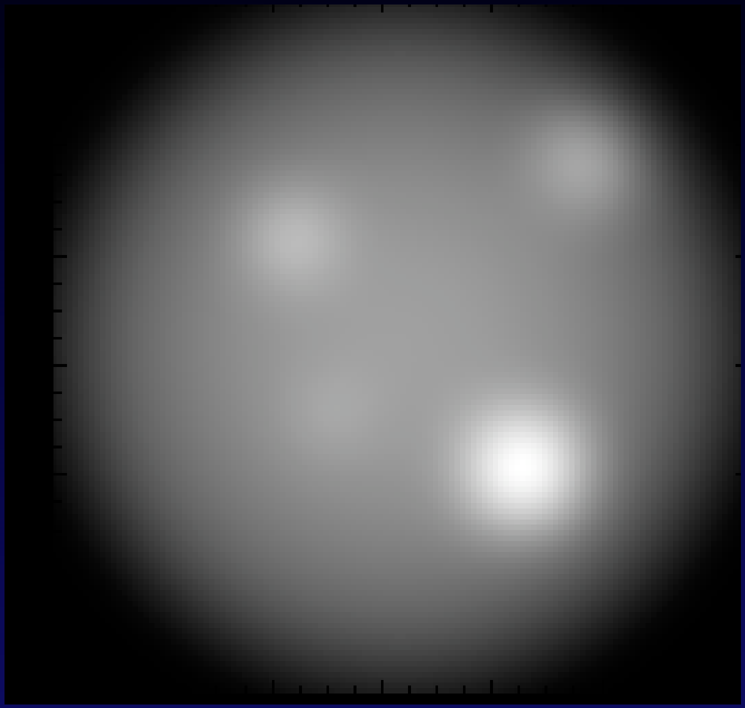


- Toy model of five large dense clumps in an infalling hot core



CO (2-1) line profiles

Model ingredients



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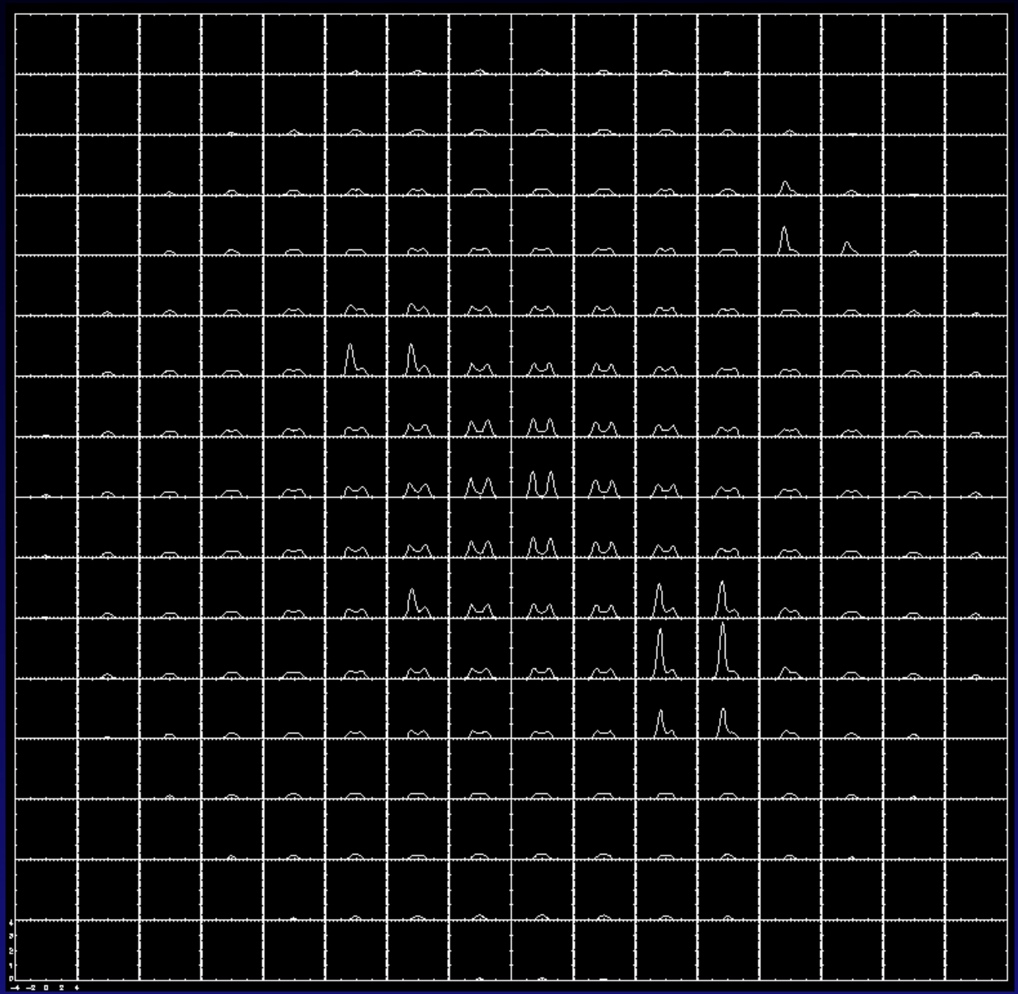


CO (4-3) line profiles

Dynamical tracer species

Molecule should faithfully trace the gas dynamics as deeply into the cloud as possible

Candidate dynamical tracer species include N_2H^+, HCO^+, HCN, NH_3, CO and others

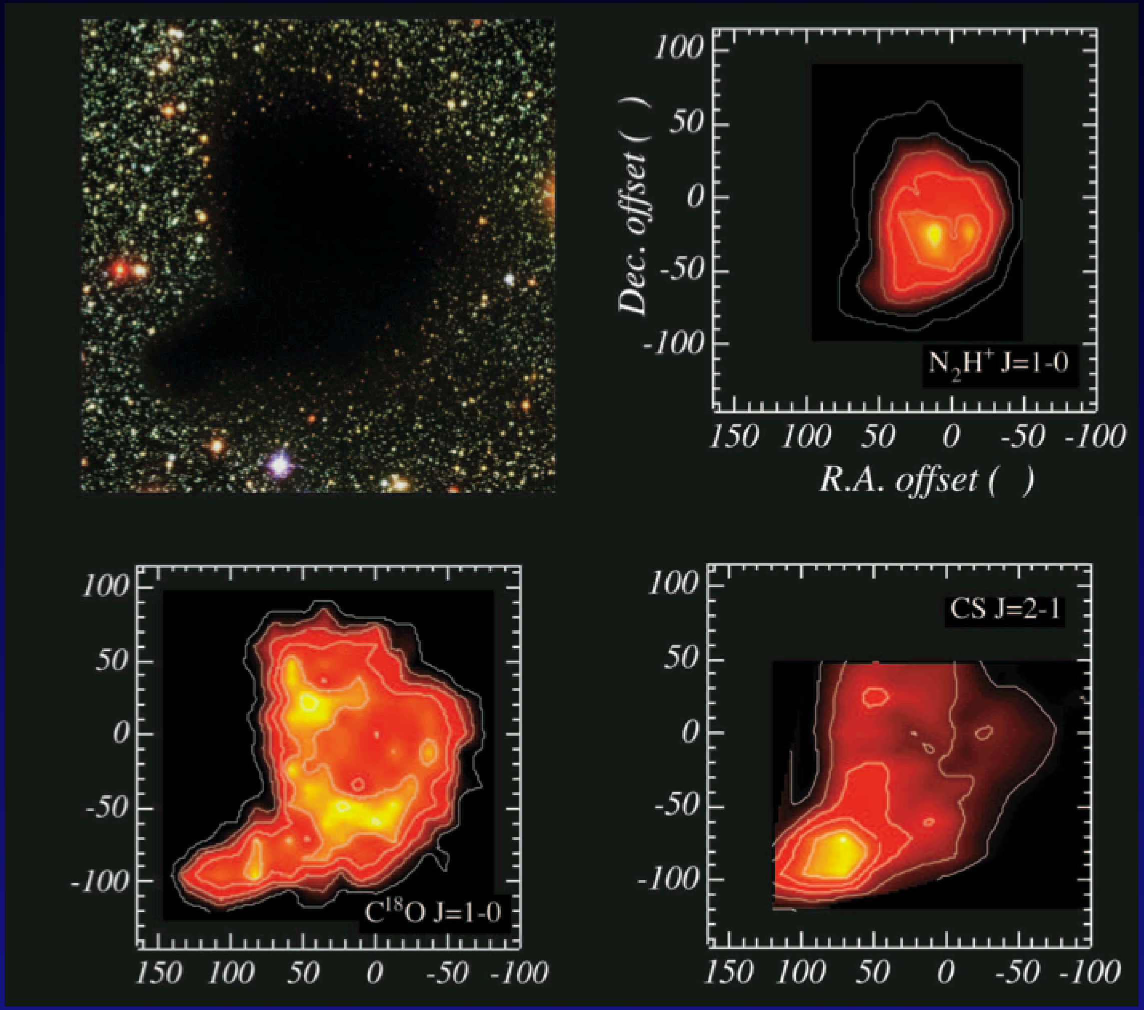
Need the abundance as a function of depth into cloud

Affected by depletion and by chemistry

Depletion in starless cores

Depletion due to freeze out seems to be common towards the centre of starless cores

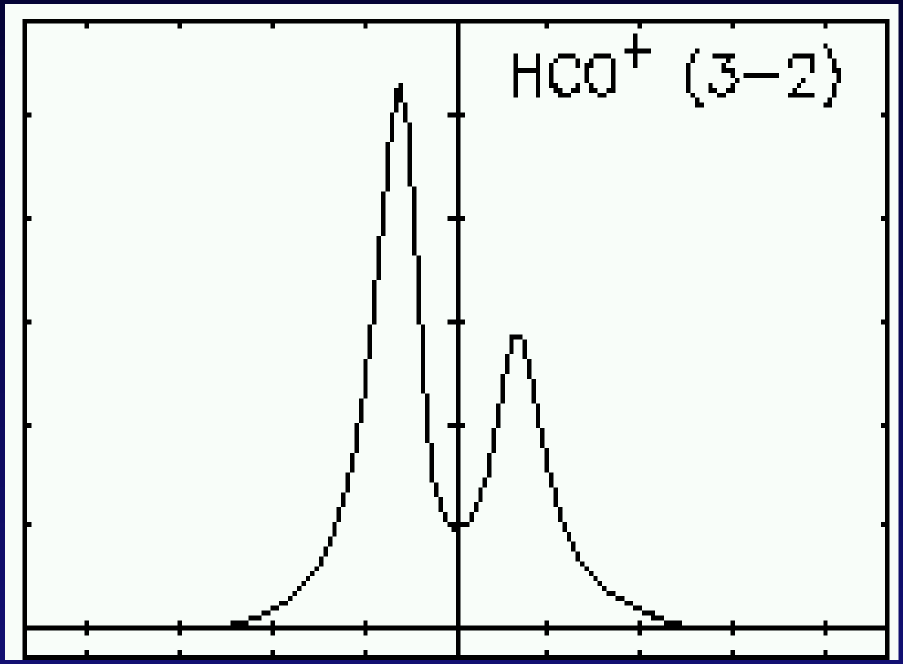
Some species appear more resistant to freeze-out such as N_2H^+ and HCN



Dynamical collapse signature

Once a starless core has lost all forms of pressure support it will begin to collapse to form a protostar

High opacity coupled with a temperature and density gradient give an characteristic infall signature

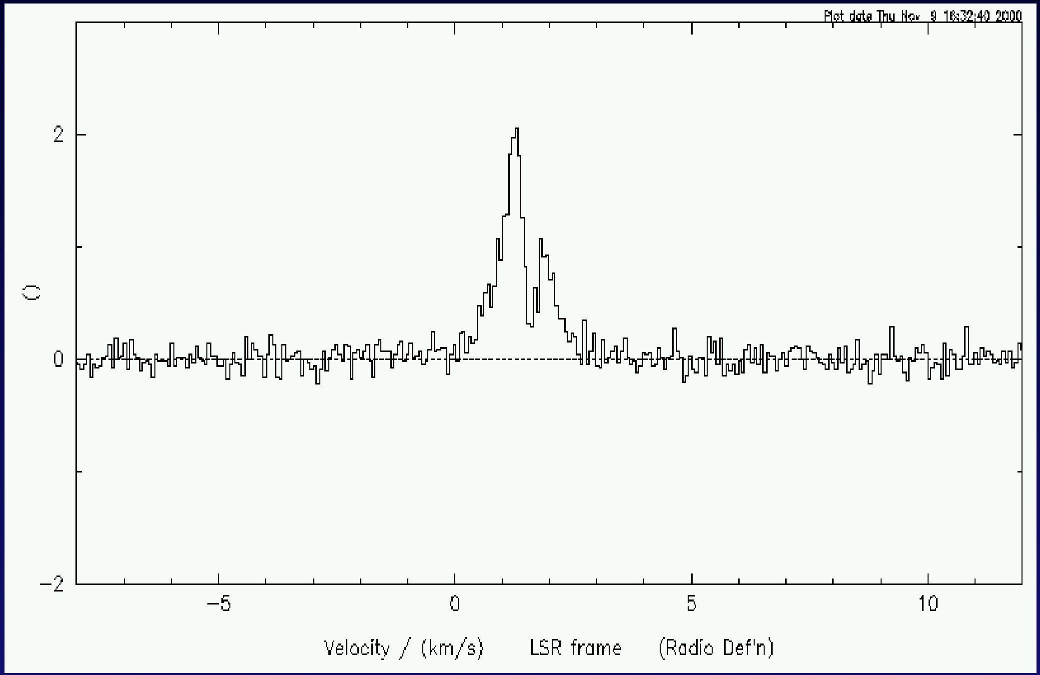


B335 HCO^+ (3-2)

Collapse signature

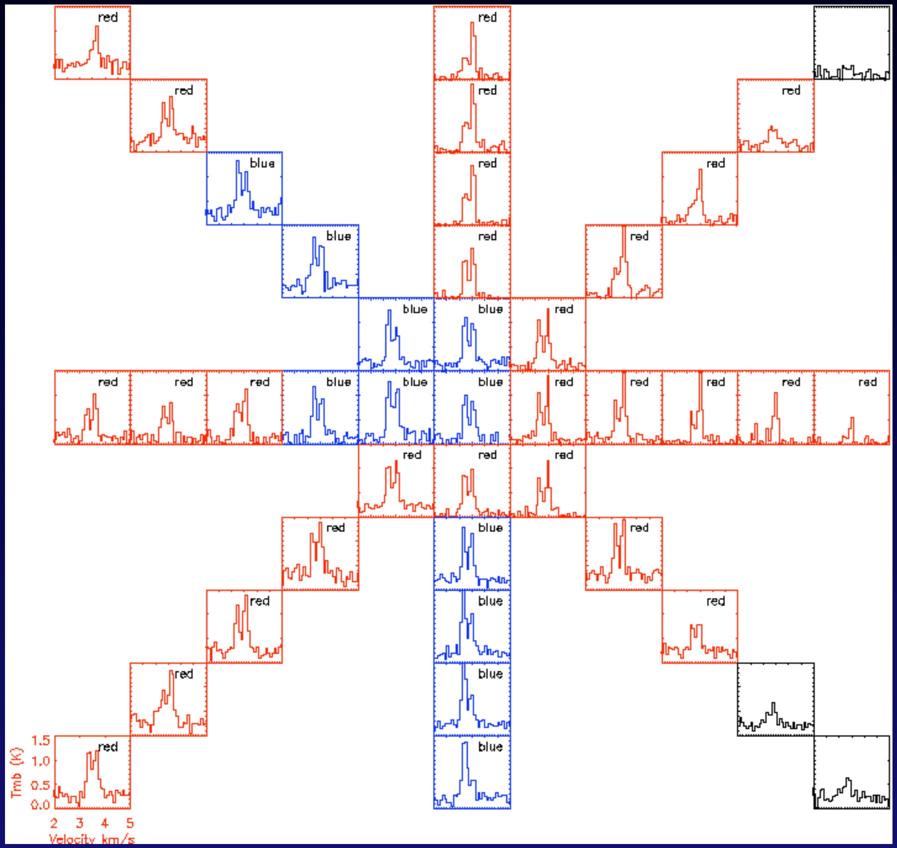
Can potentially be used to test star formation models
by giving infall velocity as a function of radius

..however, the reverse profile shape also seen



B335 HCO^+ (3-2)

Collapse signature?



Redman et al 2006

In the starless core B68, both red and blue asymmetric profiles are seen - subsonic pressure disturbances in outer layers?