Chemical Evolution of Protostars

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Outline

- Introduction
  - Molecules as probes and signposts
  - Chemical processes
- Evolution of the chemistry
  - From diffuse to dark clouds
  - …to dense cores
  - …to stars, jets, and disks
- Summary and outlook

Introduction

- Molecular lines are powerful probes of physical conditions
  - Excitation analysis
  - Velocity profiles
  - Chemical abundances
- We need to understand the chemistry to know
  - which region is traced
  - use abundances as *clocks* or *signposts* for processes

Chemical Processes

- Gas-phase chemistry
  - Two-body reactions
  - Ion-neutral reactions much more efficient than neutral-neutral
- *Chemical* time scales often comparable to *dynamical* time scales: no steady state!
- Chemical reactions in on grains allow different pathways
  - Hydrogenation
  - Activation barriers

Formation and Destruction

$X+Y \rightarrow XY^{*} \rightarrow XY+\gamma$

Radiative Association

$X+e \rightarrow X^{-}+\gamma$

$X^{-}+Y \rightarrow XY+e$

Associative Detachment

$X^{+}+e \rightarrow X+\gamma$

$XY^{+}+e \rightarrow XY+\gamma$

$XY^{+}+e \rightarrow X+Y$

Photodissociation

$X+YZ \rightarrow XY+Z$

$X^{+}+YZ \rightarrow XY^{+}+Z$

Neutral-neutral and ion-neutral reactions

$X+g:Y \rightarrow X:g:Y \rightarrow g:XY \rightarrow g+XY$

Grain-surface reactions

Many chemical pathways start with $\mathcal{CR}$-formation of H_3^+

$H_2 + \mathcal{CR} \rightarrow H_2^+ + e$

$H_2^+ + H_2 \rightarrow H_3^+ + H$

$H_3^+ + CO \rightarrow HCO^+ + H_2$

$H_3^+ + N_2 \rightarrow N_2H^+ + H_2$

Deuterium-exchange leads to high levels of deuteration in cold gas, $>10^4$ over cosmic

$H_3^+ + HD \leftrightarrows H_2D^+ + H_2$

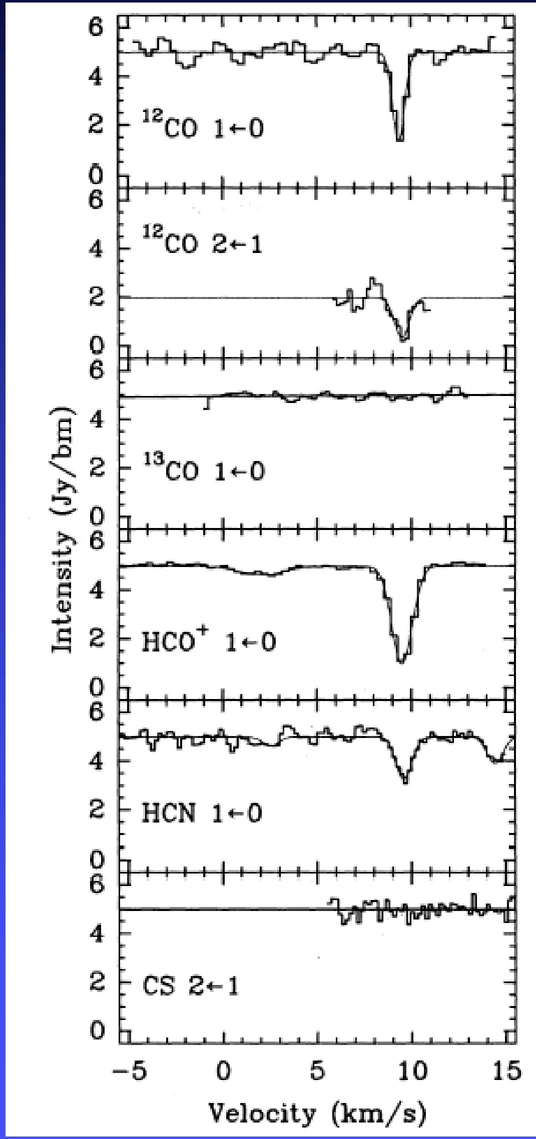
20 K

Modeling the chemistry

- Gas-phase reaction networks
  - E.g., UMIST rate99
  - 4000 reactions, 400 species, 12 elements
  - www.rate99.co.uk
- Include grains-surface reactions
  - Need to know sticking probability
  - Need to know desorption mechanisms
- Time dependent models (fixed depth)
- Depth dependent models (steady state)
- *Combined* approach within hydrodynamical framework (e.g., Markwick et al. 2002)

Diffuse Clouds

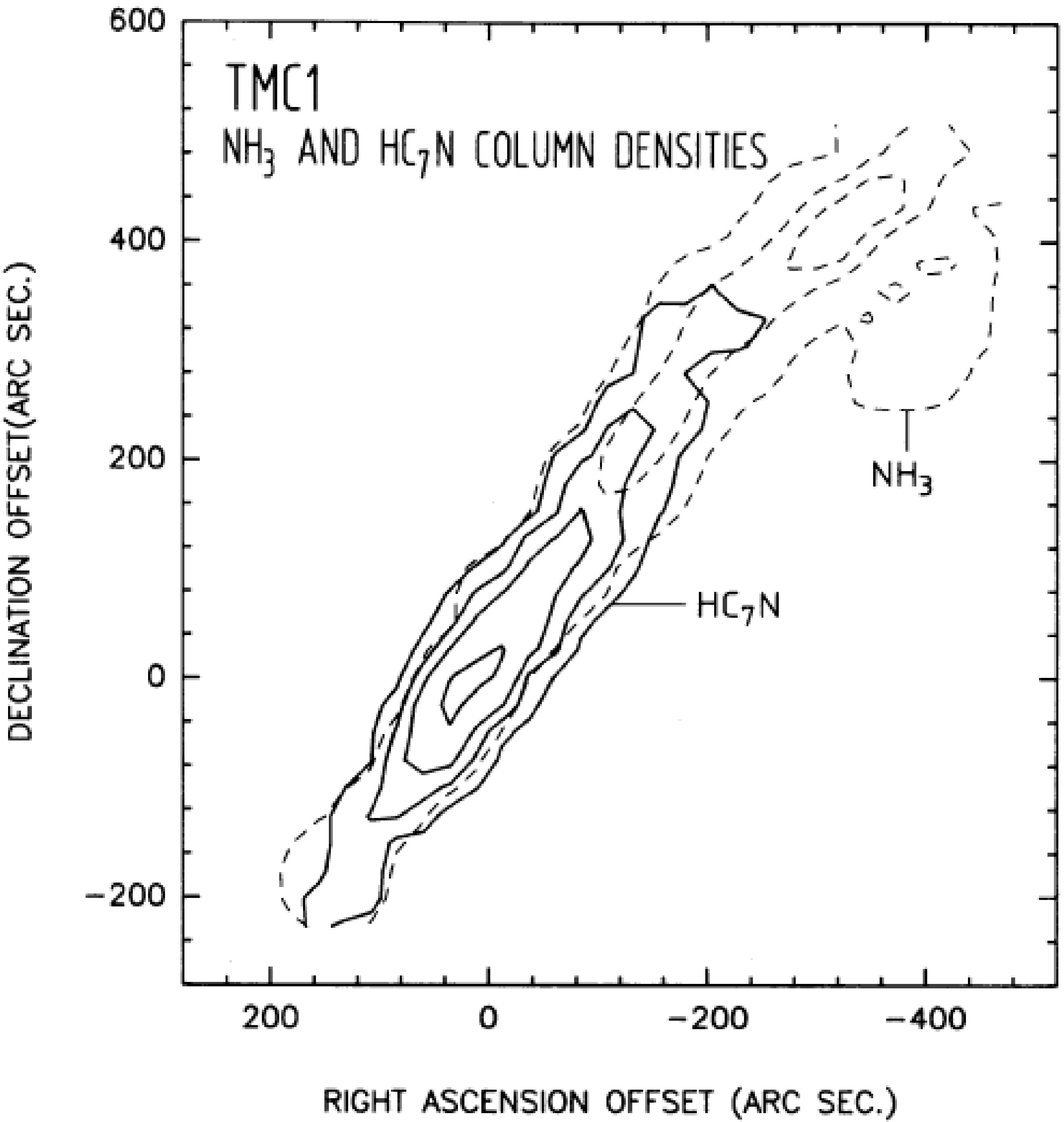
- A_V~few magnitudes
- Densities < few thousand H_2 cm^{-3}
- Poorly shielded against UV
- Abundances in general well explained by standard ion-molecule chemistry (Turner et al. 1998)
- Except NH_3, H_2CO, H_2S
  - Formed on grains?
  - Desorption mechanism?
- Except CH_4, HCO^+
  - Shocks? Turbulence?



(Hogerheijde et al. 1995)

Dark Molecular Clouds

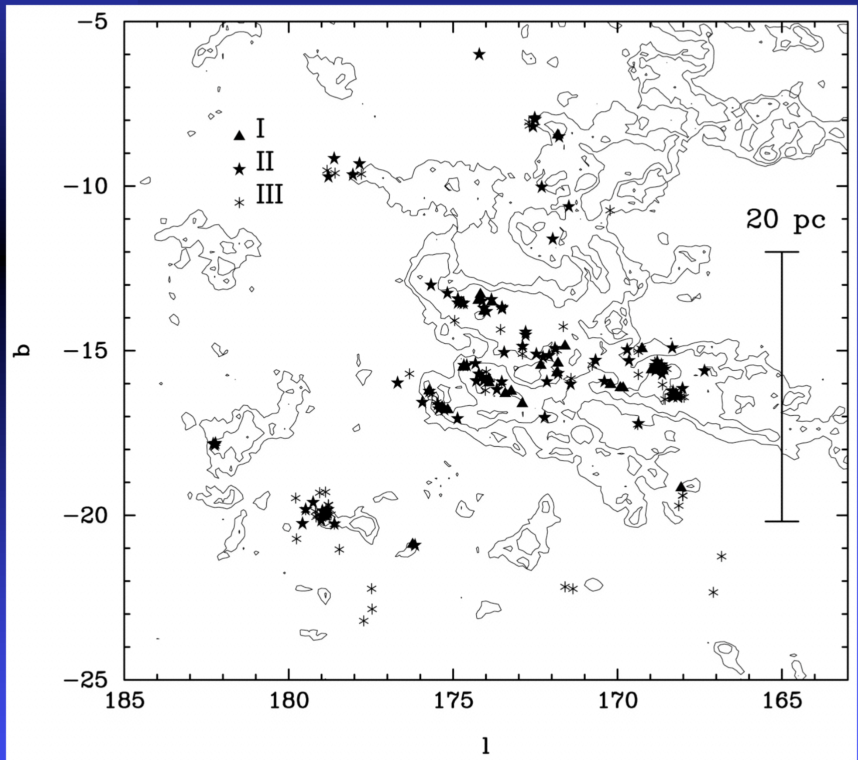
- A_V> a few magnitudes
- Larger densities
- Lower temperatures
- Species shielded against UV
  - More complex species, carbon chains
  - Chemical gradients
    - Evolution?
    - Density?
    - Hydrodynamics, turbulence?

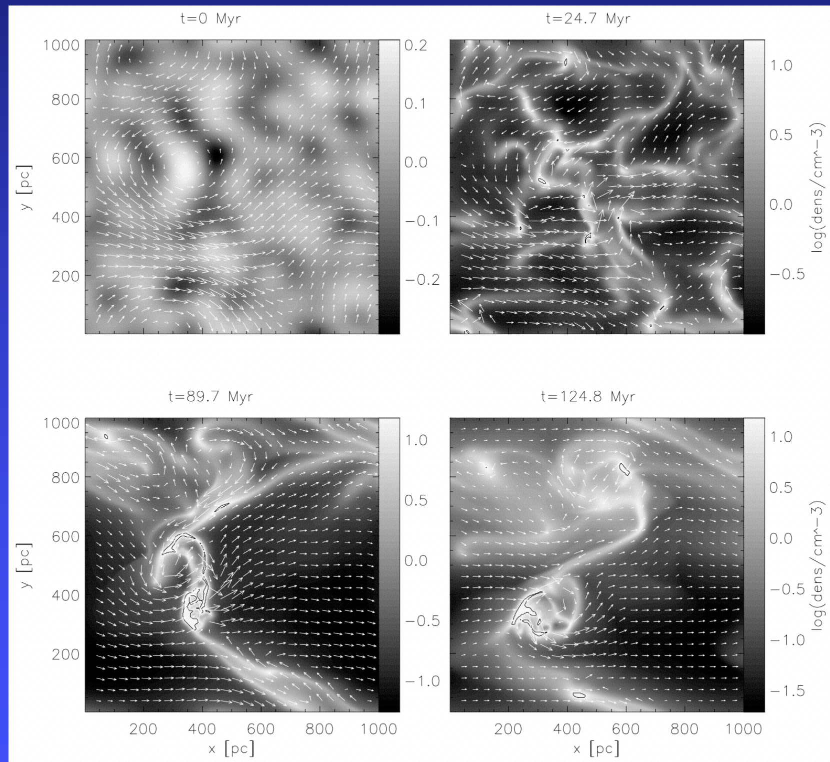


Olano et al. 1988

Longevity (>free-fall time) of molecular clouds challenged by Hartmann et al. (2001)

–Quick formation of H_2 (on grains)?



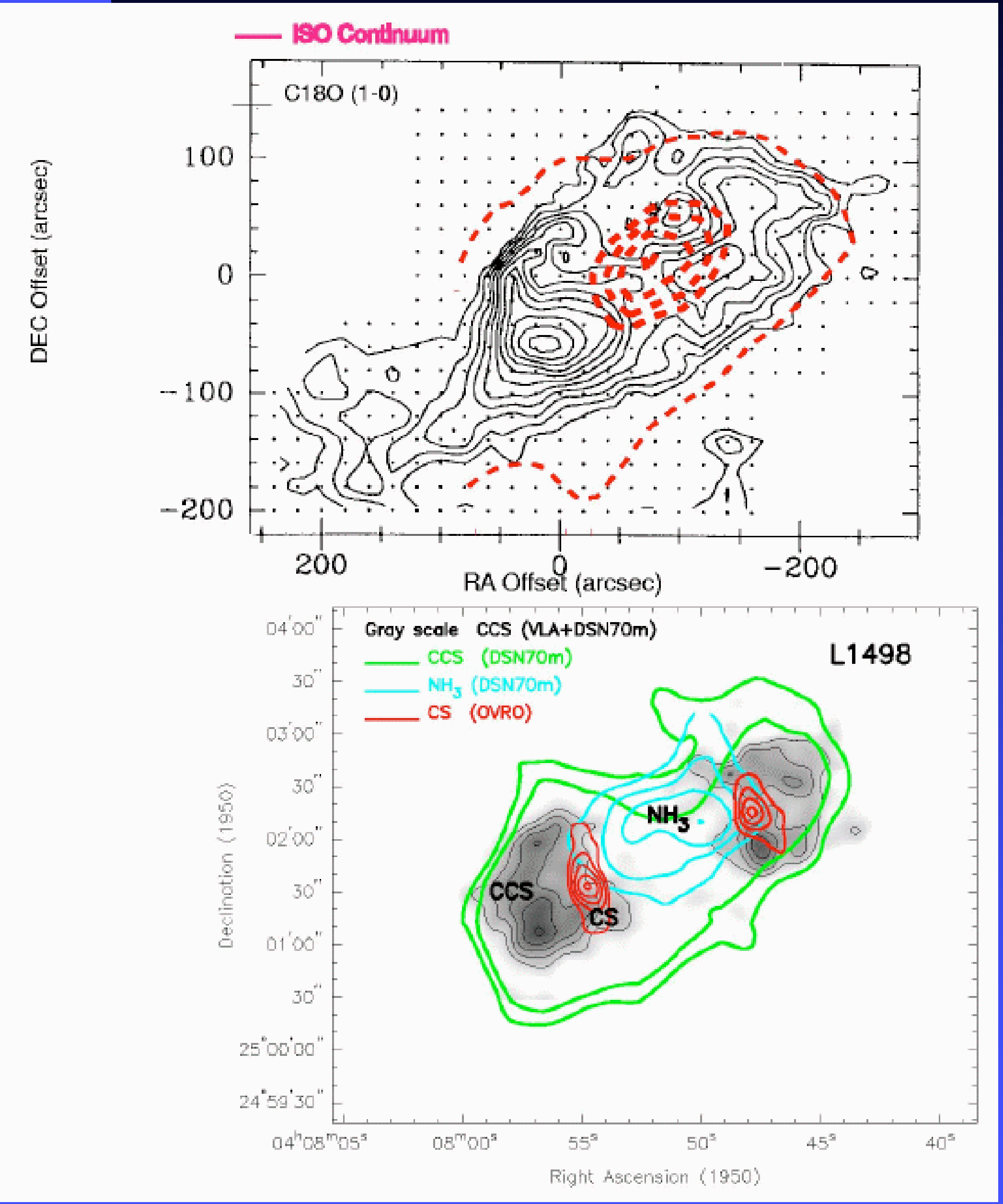


Dark Clouds and GMCs

- Two types of clouds
  - Dark molecular clouds ($M < 10^4\ M_\odot$)
  - Giant Molecular Clouds($M > 10^5\ M_\odot$)
- Different star-formation environments
  - Isolated low-mass stars (Taurus)
  - Rich clusters of many low-mass and a few high mass stars (Orion/Trapezium)
  - Intermediate environments?

Depletion

- Gas phase molecules can stick onto grains
- Inside dark cloud condensations, densities increase and temperatures drop
- Resulting freeze-out time scale < dynamical time scale of the core
- Many species disappear from the gas phase



L1498 – starless core

(Kuiper et al. 1996)

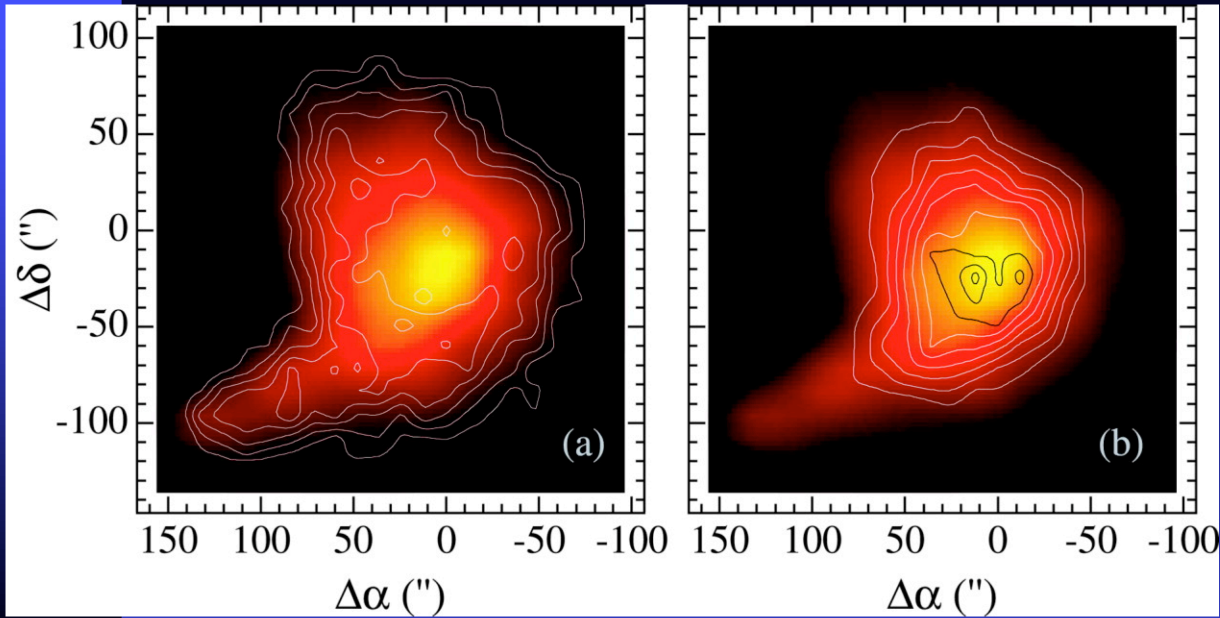
Late depleter: N_2H^+

$$H_3^+ + N_2 \rightarrow N_2H^+ + H$$

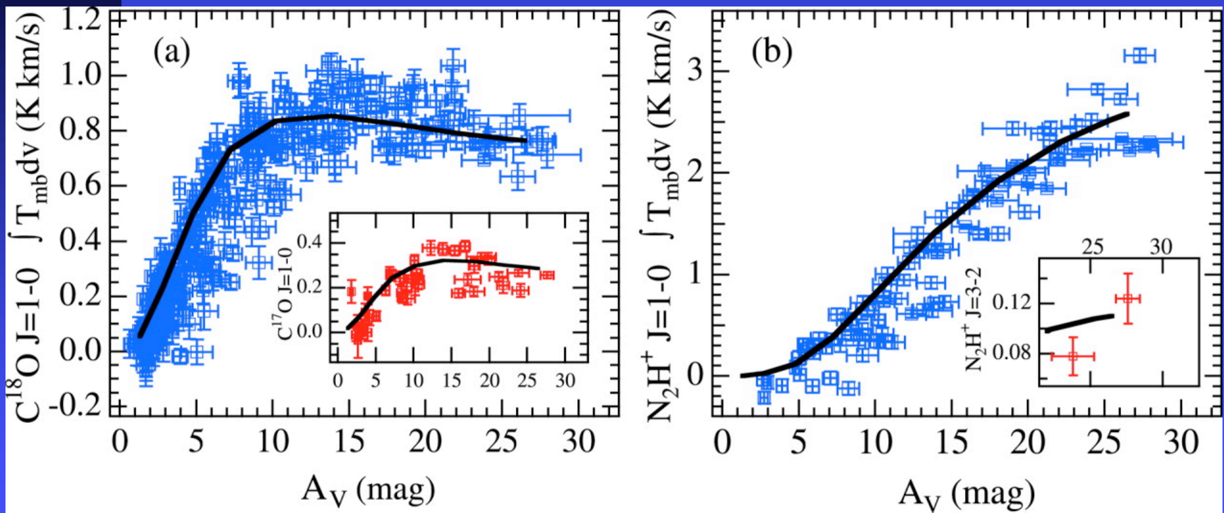
$$N_2H^+ + CO \rightarrow N_2 + HCO^+$$

$$N_2H^+ + H_2O \rightarrow N_2 + H_3O^+$$

- ◆ $\mathcal{CR}$ can penetrate deep into cloud
- H_3^+ remains abundant
- N_2 not *thought* to deplete
- CO and H_2O deplete
- N_2H^+ abundant



$C^{18}O$ N_2H^+



Starless core B68

Bonnor-Ebert sphere

Even N_2 depletes?

(Bergin et al. 2002)

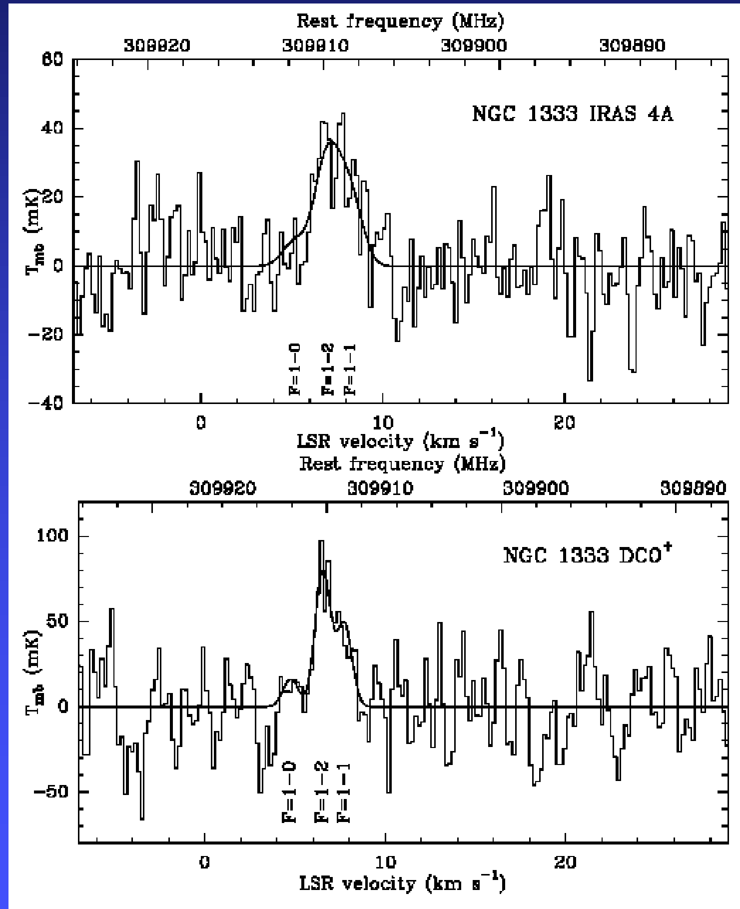
Depletion leads to deuteration

$H_3^+ + HD \leftrightarrows H_2D^+ + H_2$

ND_3 in NGC1333 IRAS4

$NH_3/ND_3=1000$

 D/H=0.15



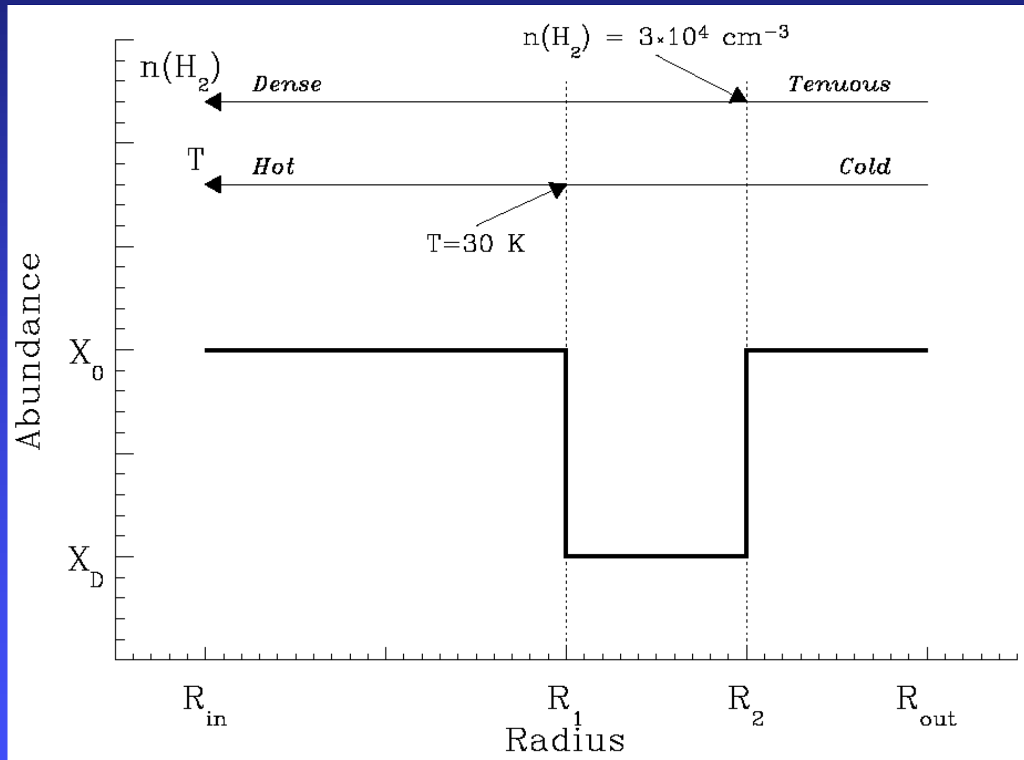
(van der Tak et al. 2002)

Near young star, ices evaporate

>20 K for CO

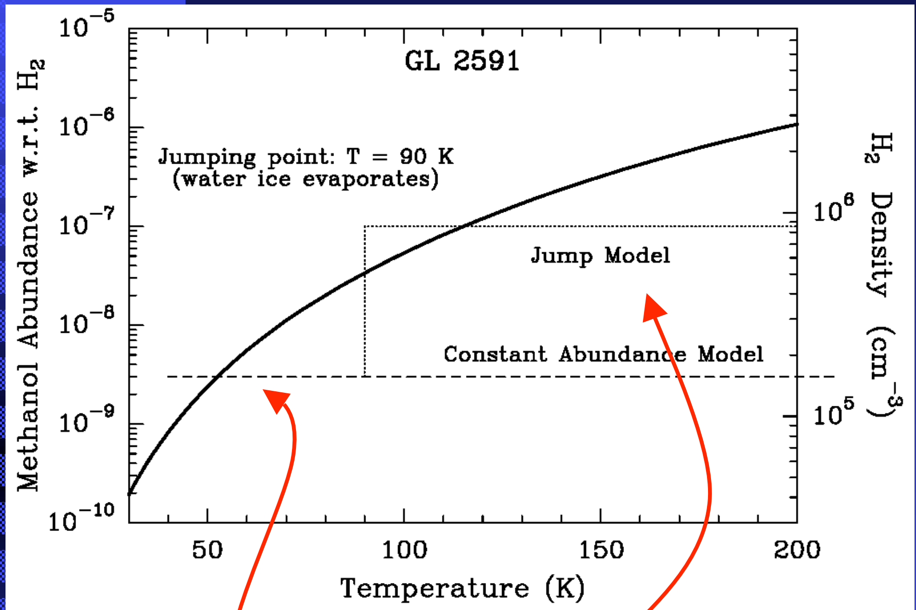
>90 K for H_2O

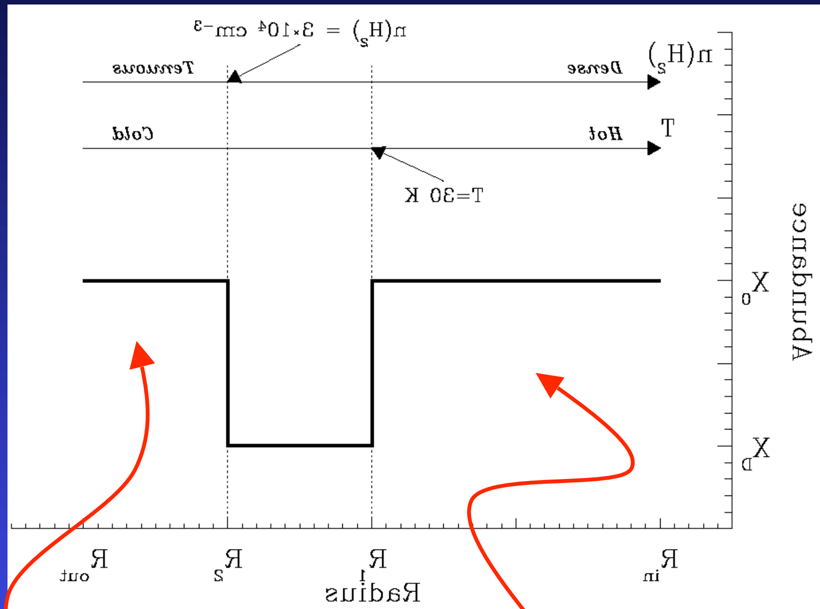
'Drop' abundances (Jørgensen et al. 2004)



Successfully explain abundances of species toward deeply embedded and more evolved *low-mass* stars

Jump vs *Drop* models





Warm inside

Warm inside

Tenuous outside

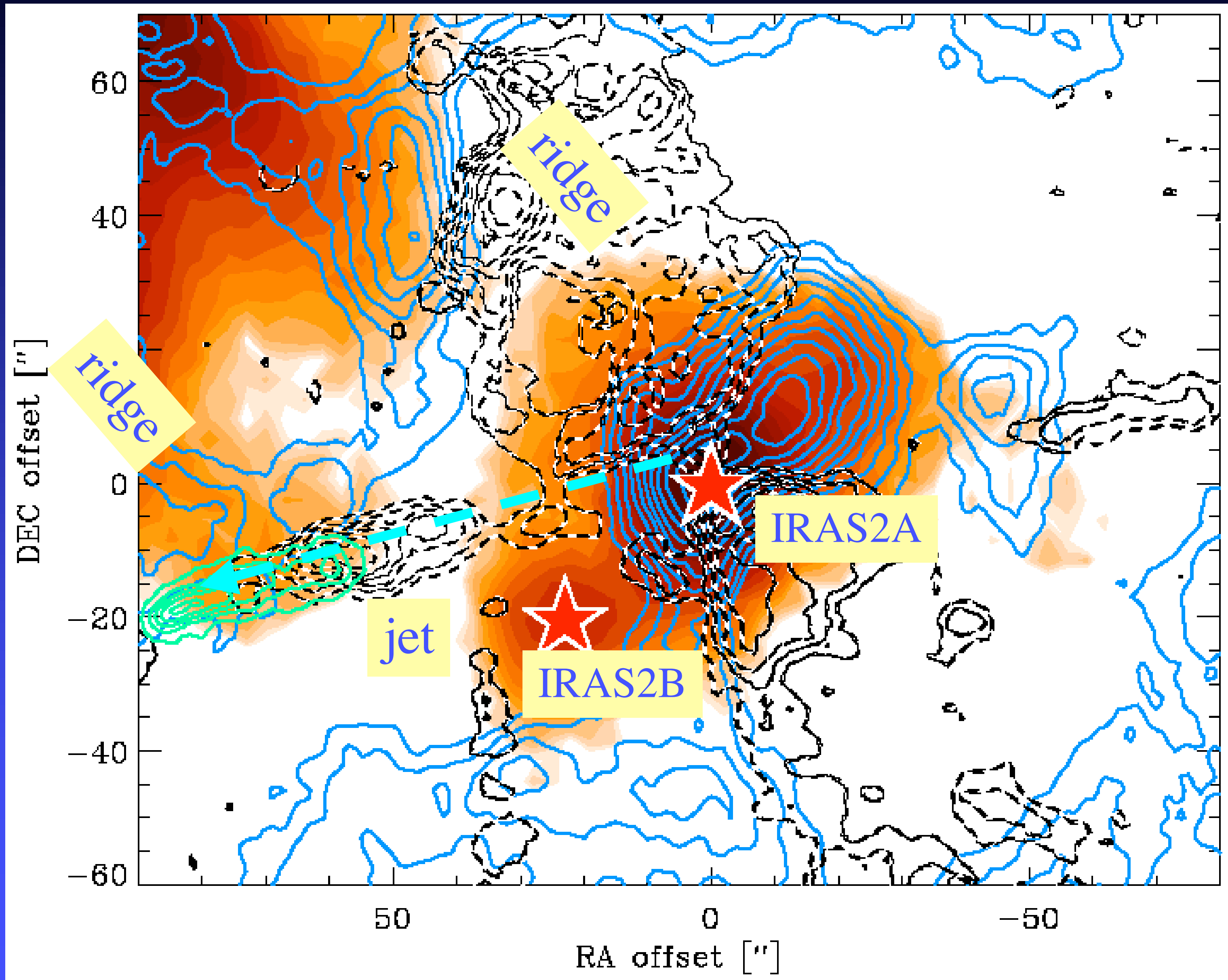
Cold outside

van der Tak et al. (2000); Jørgensen et al. (2004)

Outflows

- All low-mass stars drive outflows
- Shocks and/or advection heats material
  - Shock tracers: SiO, SO, SO_2
  - Warm-gas tracers: HCN, CH_3OH

NGC 1333 IRAS 2

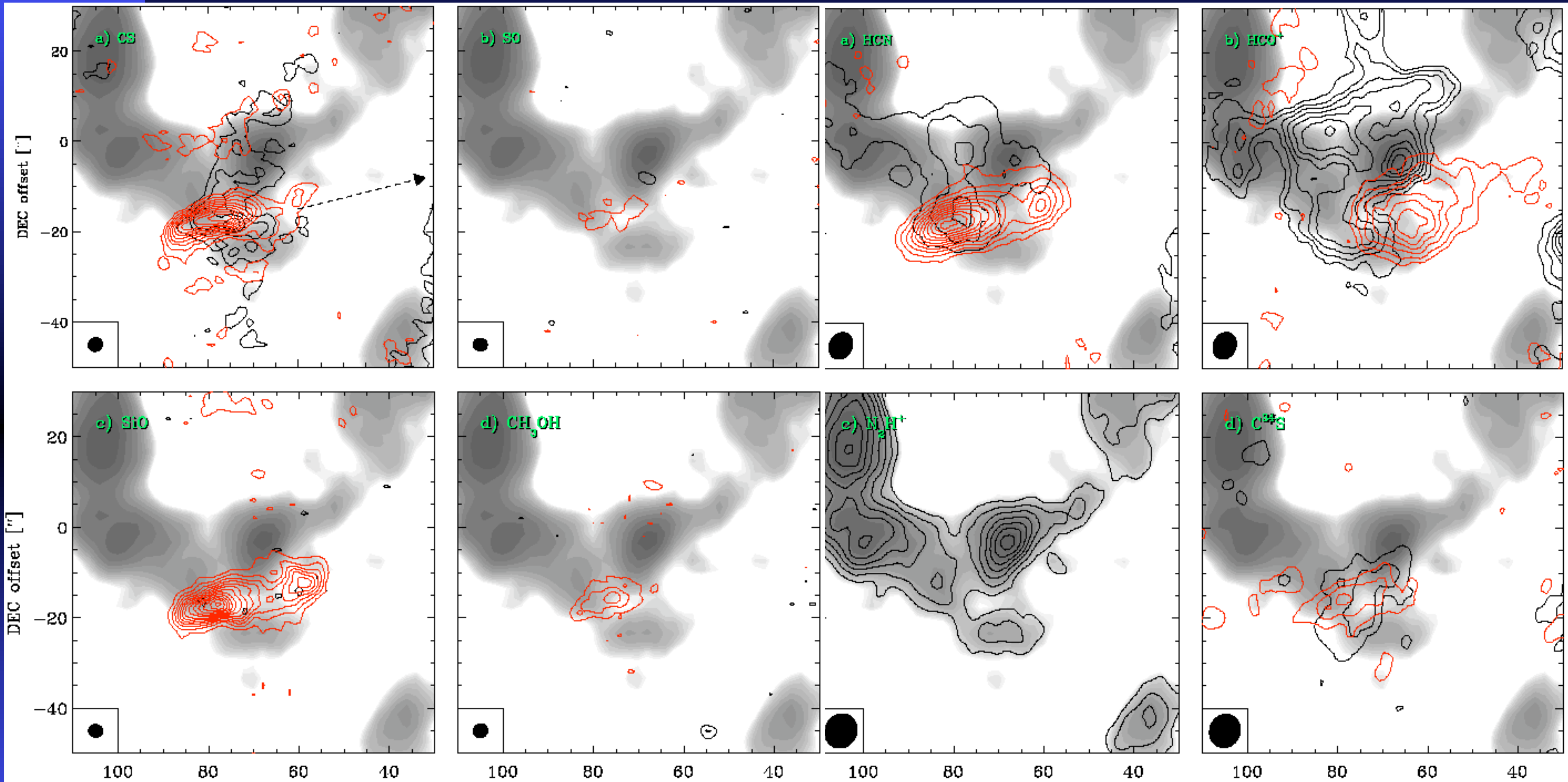


(Jørgensen et al. 2004)

Low velocity material

High velocity material

CN SO HCN HCO^+



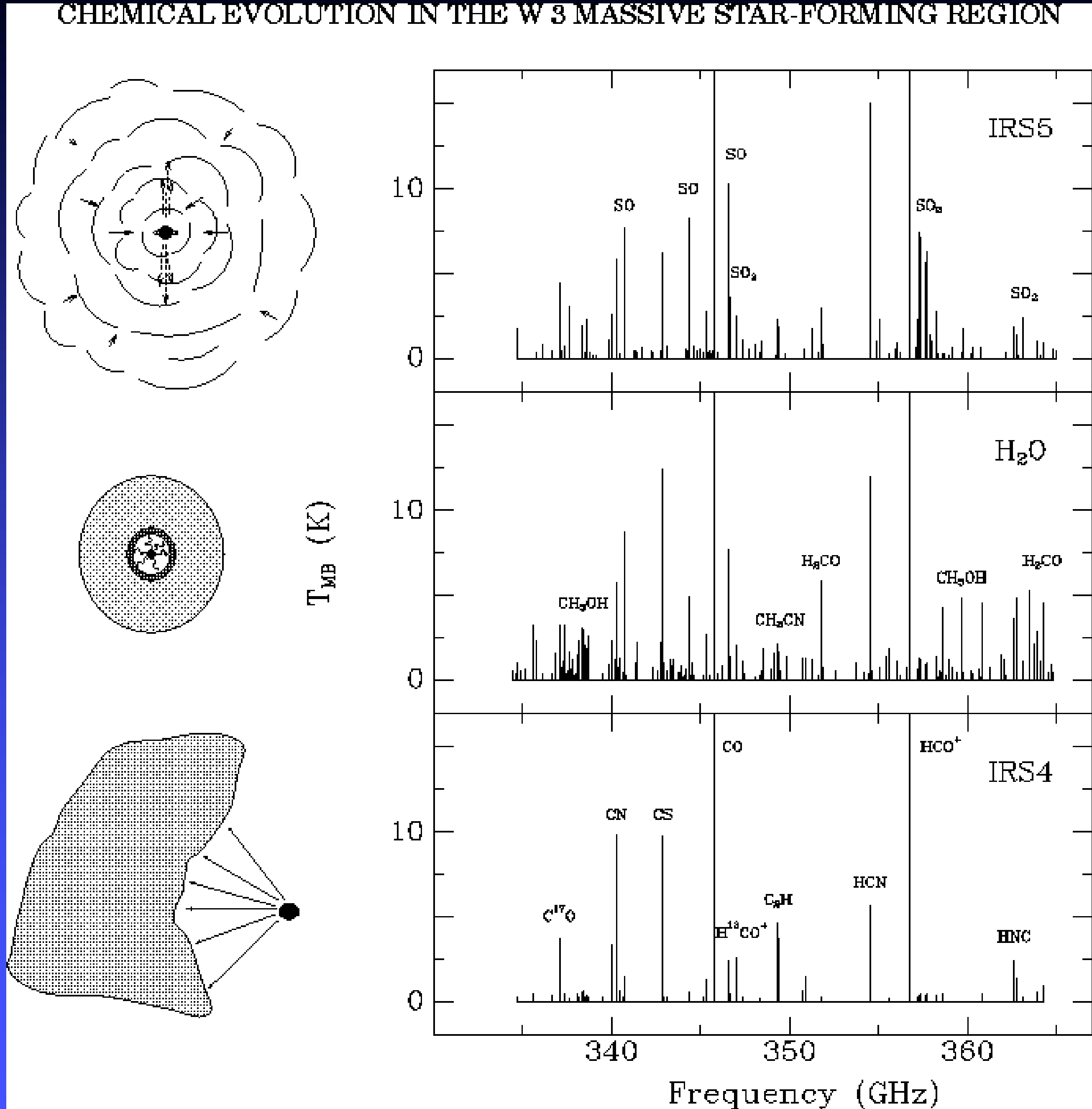
SiO CH_3OH N_2H^+ (also: greyscale) $C^{34}S$

(Jørgensen et al. 2004)

Massive star formation

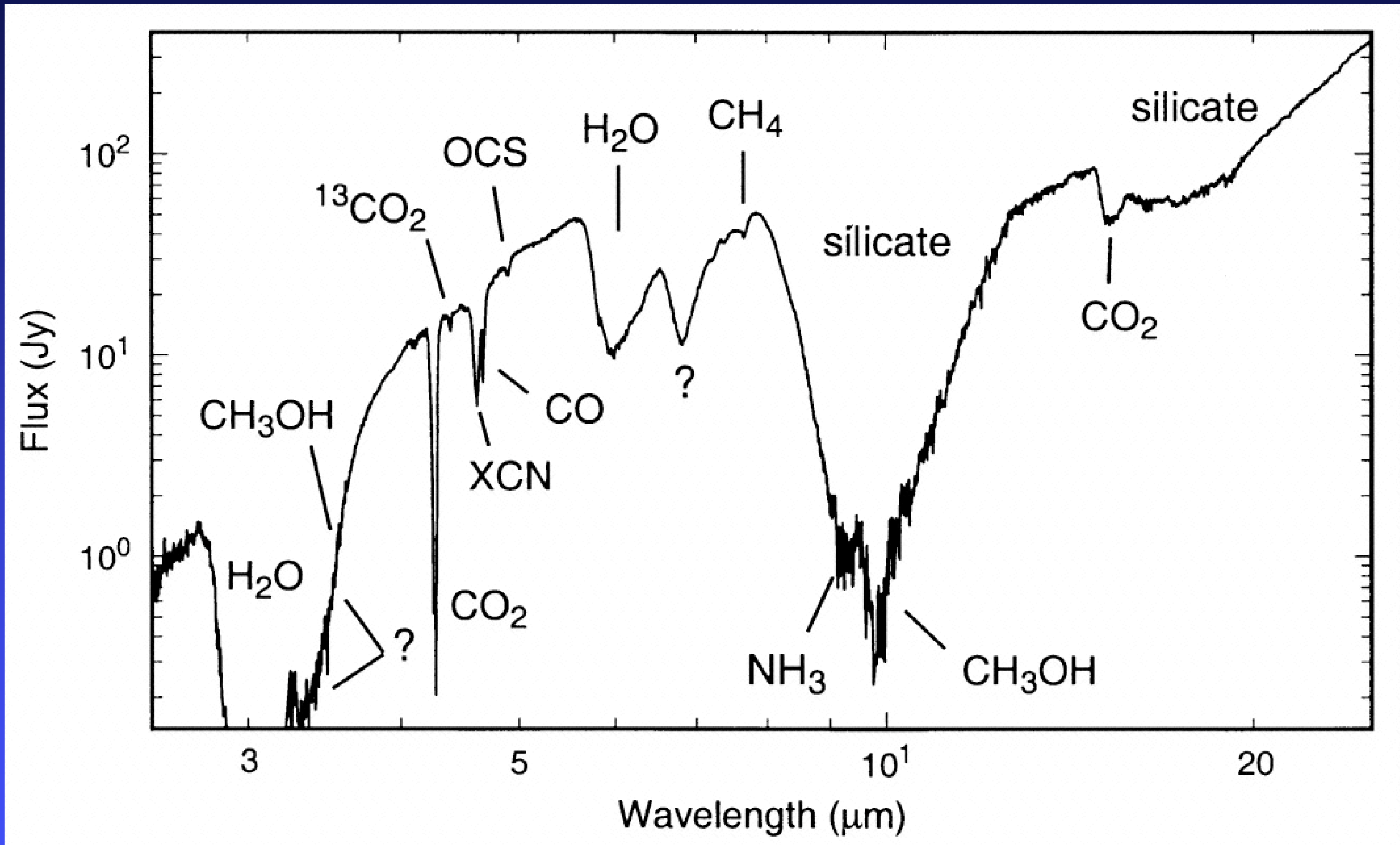
- Much less well understood than low-mass star formation
  - Occurs deep inside clouds
  - Typically further away
  - Confusing regions
- Luminosity much higher
  - Earliest appearance as hot core
  - Chemical clocks
  - Later stages: photodissociation: UCHIIs, etc.

time



(Helmich 1996)

IR absorption by ices – surface & UV chemistry

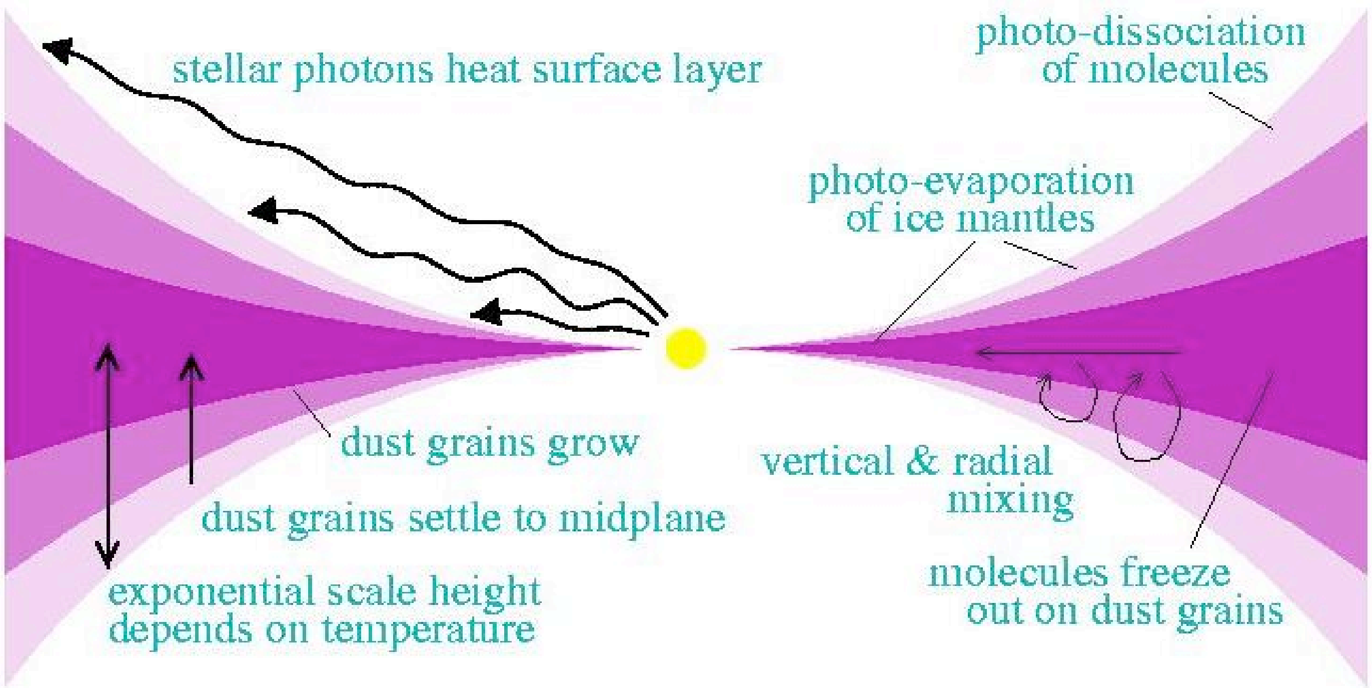


W33A – Gibb et al.(2000)

Protoplanetary disks

- Low-mass stars (and maybe higher mass stars too) often surrounded by disks.
- 'Miniature' versions of chemistry
  - Depletion in dense and cold midplane
  - Evaporation of ice mantles close to star
  - Photochemistry in 'atmosphere'
- Line emission typically traces warm layers at intermediate height, but no limits on vertical, radial mixing

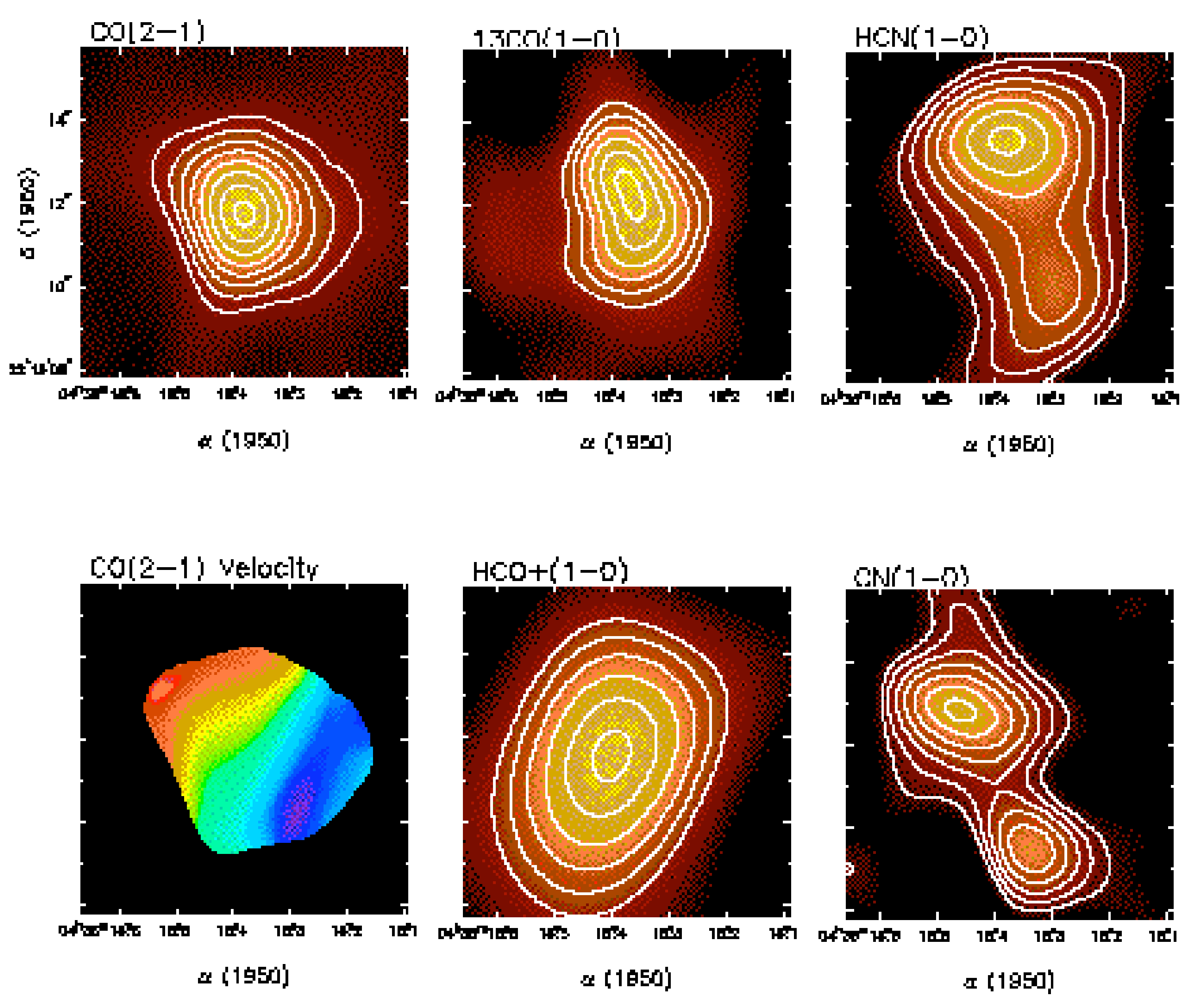
Models of circumstellar disks



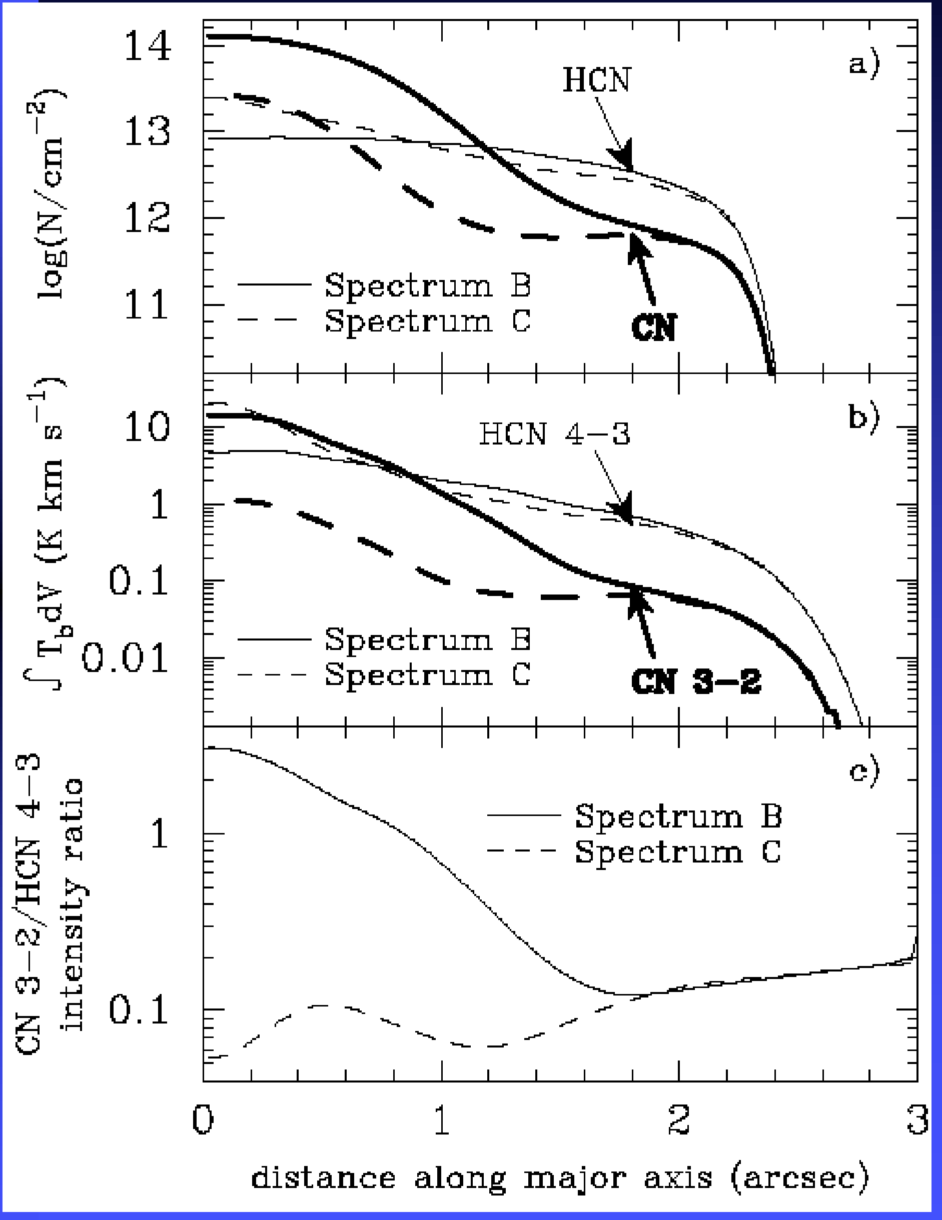
(Chiang & Goldreich 1997)
(d'Alessio et al. 1998)

(Aikawa & Herbst 1999)
(Willacy & Langer 2000)

LkCa15



(Qi 2001)



B = C + accretion UV
C = 4000 K black body

CN / HCN ratio traces stellar UV spectrum = accretion activity

van Zadelhoff et al. (2003)

Summary

- Competing processes of
  - Photodissociation
  - Chemistry
  - Depletion
  - Evaporation
- Differences in luminosity lead to very different *apparent* chemistries between high and low-mass stars

Outlook

- Much has been learned from submillimeter instruments such as JCMT, CSO, OVRO, BIMA, PdBI
- APEX, SMA, e-SMA, CARMA, and ultimately ALMA will further our knowledge
- *Higher excitation* regimes become more easily available: warmer, denser gas traced
- *Higher angular resolutions* will resolve disks around low-mass stars and the complex environs of high-mass stars