Molecular line emission from a PPD irradiated by a nearby massive star

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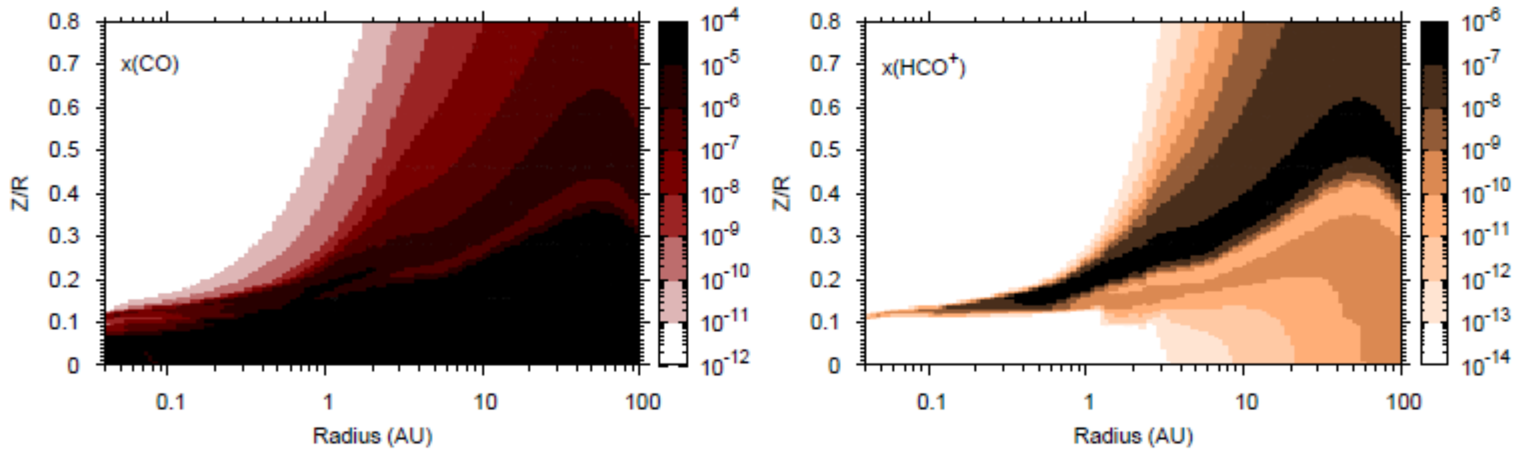
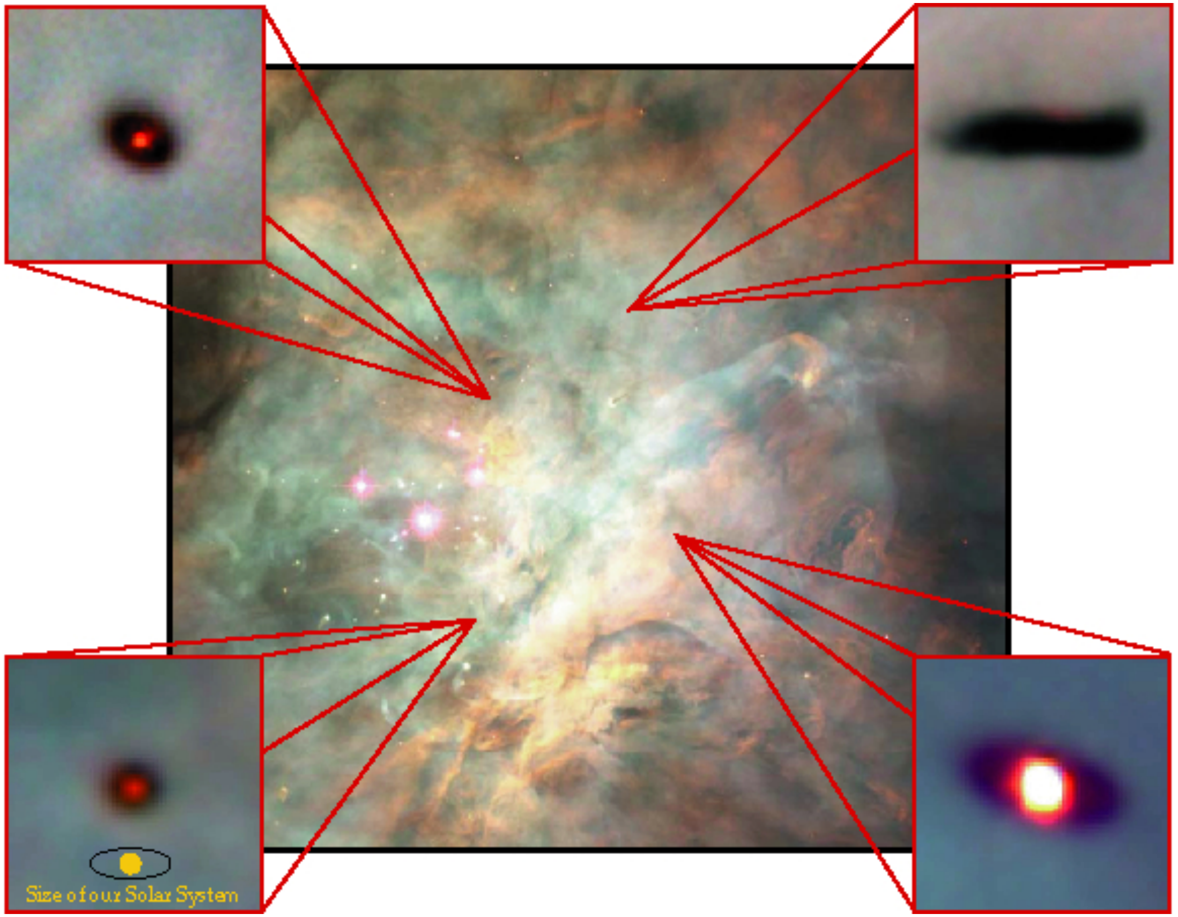


Walsh, Millar & Nomura, ApJL, 766, L23 (2013)

P27: Motoyama et al. – importance of FUV
P29. Tamura et al. – disks shrink to tens of AU in 1 Myr

Protoplanetary Disks

Observed directly around low-mass protostars



Essentially an engine that:
(i)Allows mass to be accreted on to a central object – a newly-forming star
(ii)Allows angular momentum to be transported outwards
(iii)Provides the material out of which stars and planetary systems form
(iv)Often situated in regions of high external UV flux

Molecular Emission in Proplyds

- A good physical model – stellar properties, mass accretion rate, dust properties, stellar and interstellar UV, stellar Lyman alpha radiation, CR, X-ray fluxes, geometry, irradiation from a nearby O-type star

- A good chemical model – reaction rates including high T and 3 body rates, gas-grain interchange, surface chemistry, .. (UMIST Database for Astrochemistry)

- A good radiative transfer model – UV photons (input radiation), IR and (sub)millimeter photons (output radiation), collisional & radiative rate coefficients,..

Chemistry in PPDs

Walsh, Millar & Nomura 2010, ApJ, 722, 1607

Heinzeller, Nomura, Walsh & Millar, 2011, ApJ, 731, 115

Walsh, Nomura, Millar & Aikawa 2012, ApJ, 747, 114

Large gradients in physical parameters give rise to small scale abundance and emission variations

Protoplanetary Disk Model

- Physical Model
  - Nomura & Millar, 2005 and Nomura et al., 2007 – constrained by observations of H_2
  - 2-D temperature and density distribution
  - 2-D UV and X-ray radiation fields
  - Over 10,000 grid points modeled in the range 0.4 – 100 AU
  - 0.5 solar mass T Tauri star, T_{eff} = 4000K, mass accretion rate = 10^{-8} solar masses per year, α = 0.01
  - O-star, T_{eff} = 45000K, UV flux at disk surface = 4 10^5 x IS flux, d ~ 0.1pc
  - Assumed hydrostatic equilibrium - whereas photevaporative flow could affect surface density in outer disk

- Chemical Model
  - UMIST Database for Astrochemistry (Woodall et al., 2007; http://www.udfa.net)
    - 5721 reactions involving 535 species
    - 158 grain-surface species
    - 1154 gas-grain interactions
    - 221 grain-surface reactions (including UV and X-ray interaction with mantles)
  - Accretion onto dust grains (Hasegawa et al., 1992)
  - Thermal evaporation from dust grains (Hasegawa et al., 1992)
  - Non-thermal desorption mechanisms
    - Photo-desorption (Westley et al., 1995;Oberg et al., 2007; 2009a,b; Willacy, 2007)
    - Cosmic-ray induced desorption (Leger et al., 1985; Hasegawa & Herbst, 1993)
  - Initial abundances from a dark cloud model
  - Extract abundances in proplyd at a time of one million years

- Radiative Transfer
  - Local Thermodynamic Equilibrium
  - Suitable for low transitions of simple molecules
  - Following work of Pavlyuchenkov et al., 2007
  - Assume the disk is face-on
  - Calculate emission from upper (irradiated) half of the disk
  - Standard ISM isotopic ratios for the CO isotopologues

Dust model

Dust properties affect:

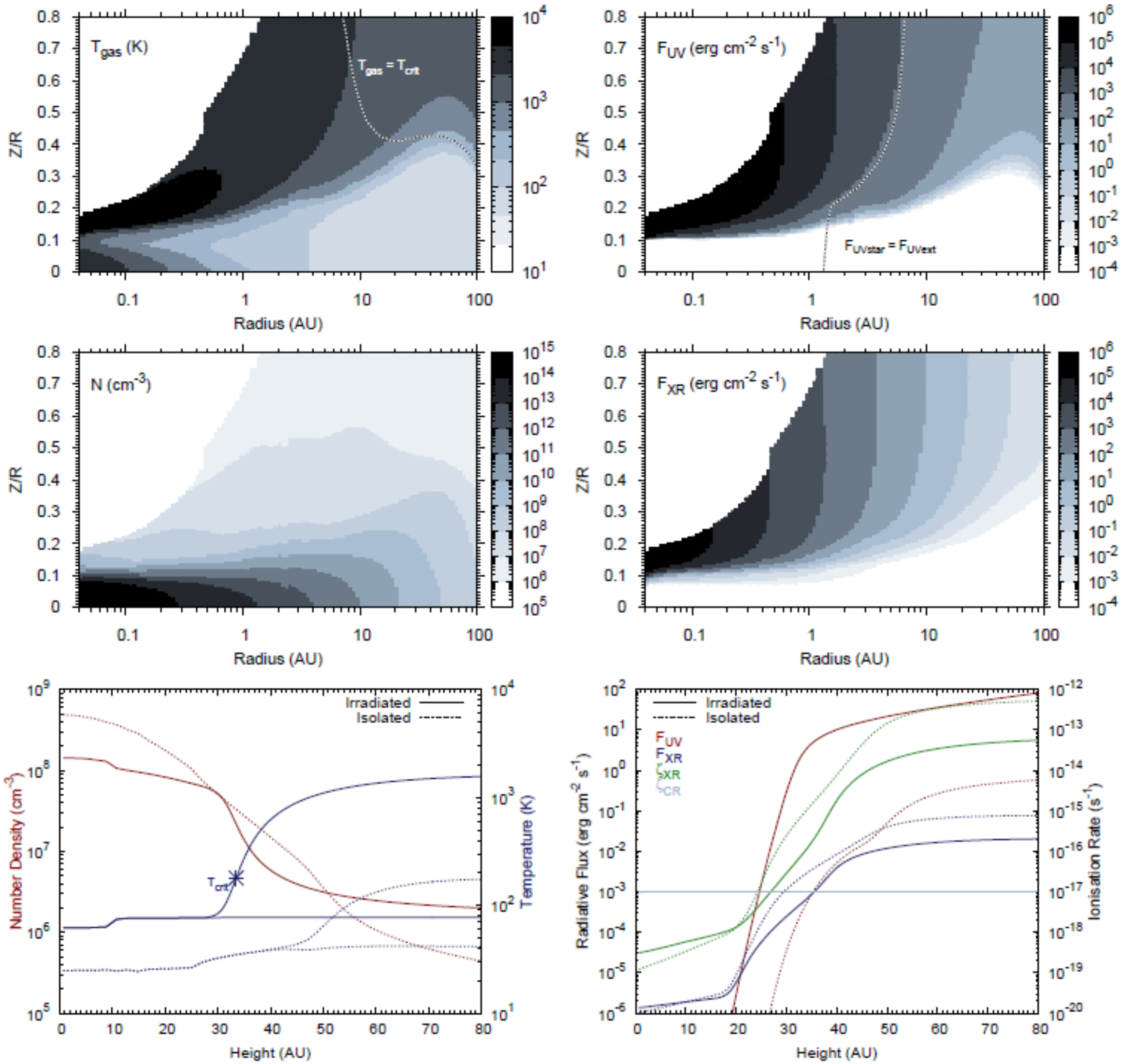
- UV intensity – absorption + scattering
- Grain temperature – re-processing stellar radiation
- Gas temperature – grain photoelectric heating and gas-grain collisions
- H/H_2 ratio – grain formation of H_2
- Excitation of H_2 on formation

Silicates, carbonaceous grains, water ice

Size distribution from Weingartner & Draine

Dust coagulation and settling are ignored

Physical parameters in the proplyd



Top Row:

Gas temperature and F_UV flux

- White lines:

T = Tcrit, the critical temperature for photoevaporation (Dullemond et al. 2007)

Central star UV flux = O-star UV flux

Middle row:

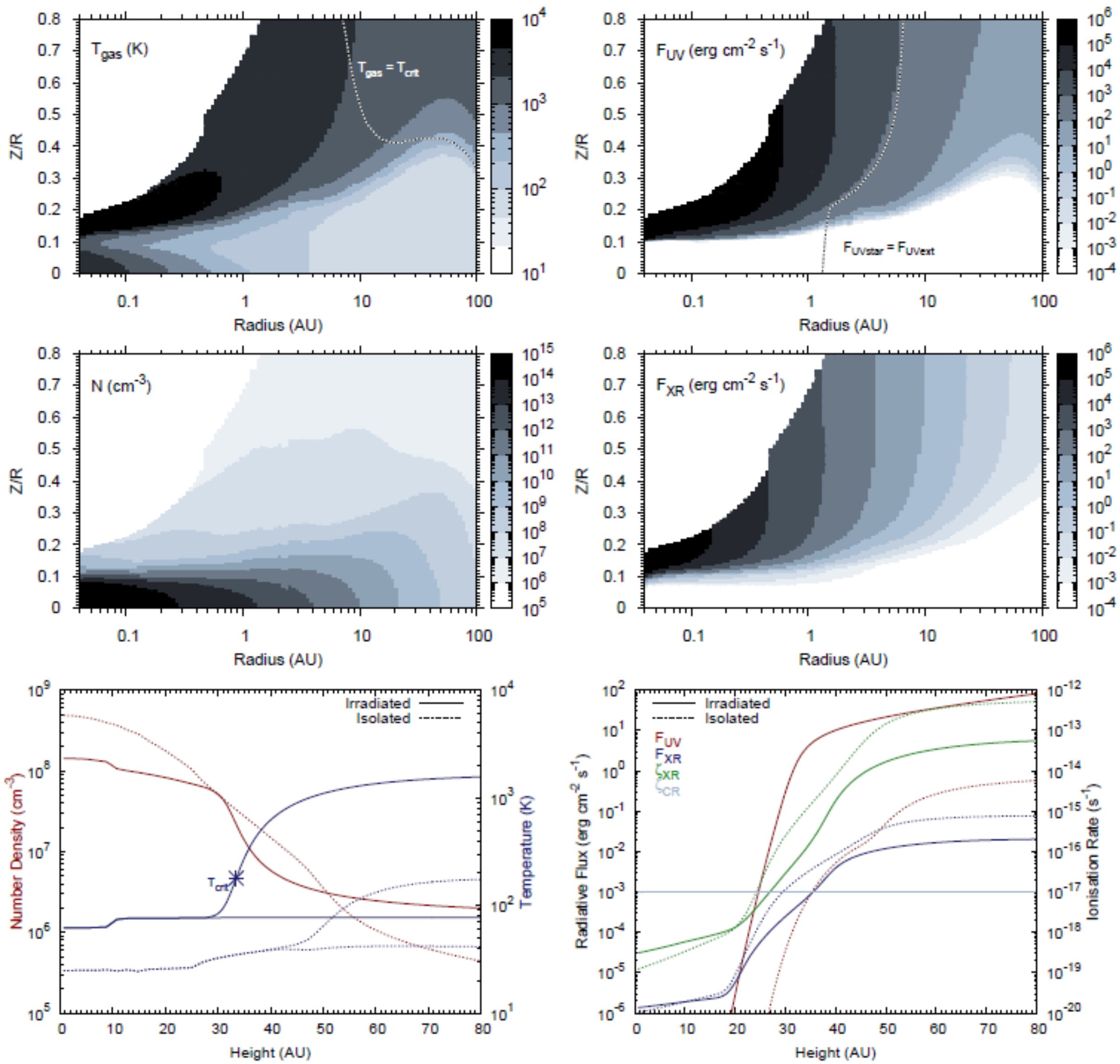
Number density and X-ray flux throughout disk

Bottom row:

Left – number density and gas and dust temperatures for irradiated (solid lines) and isolated (dotted lines) disk as function of height at 100 AU

Right – UV and X-ray fluxes and X-ray and CR ionisation rates as function of disk height at 100 AU

Physical parameters in the proplyd



Irradiated vs Isolated Disk:

Gas and dust temperatures significantly higher beyond 1 AU (inner disk dominated by heating from central star)

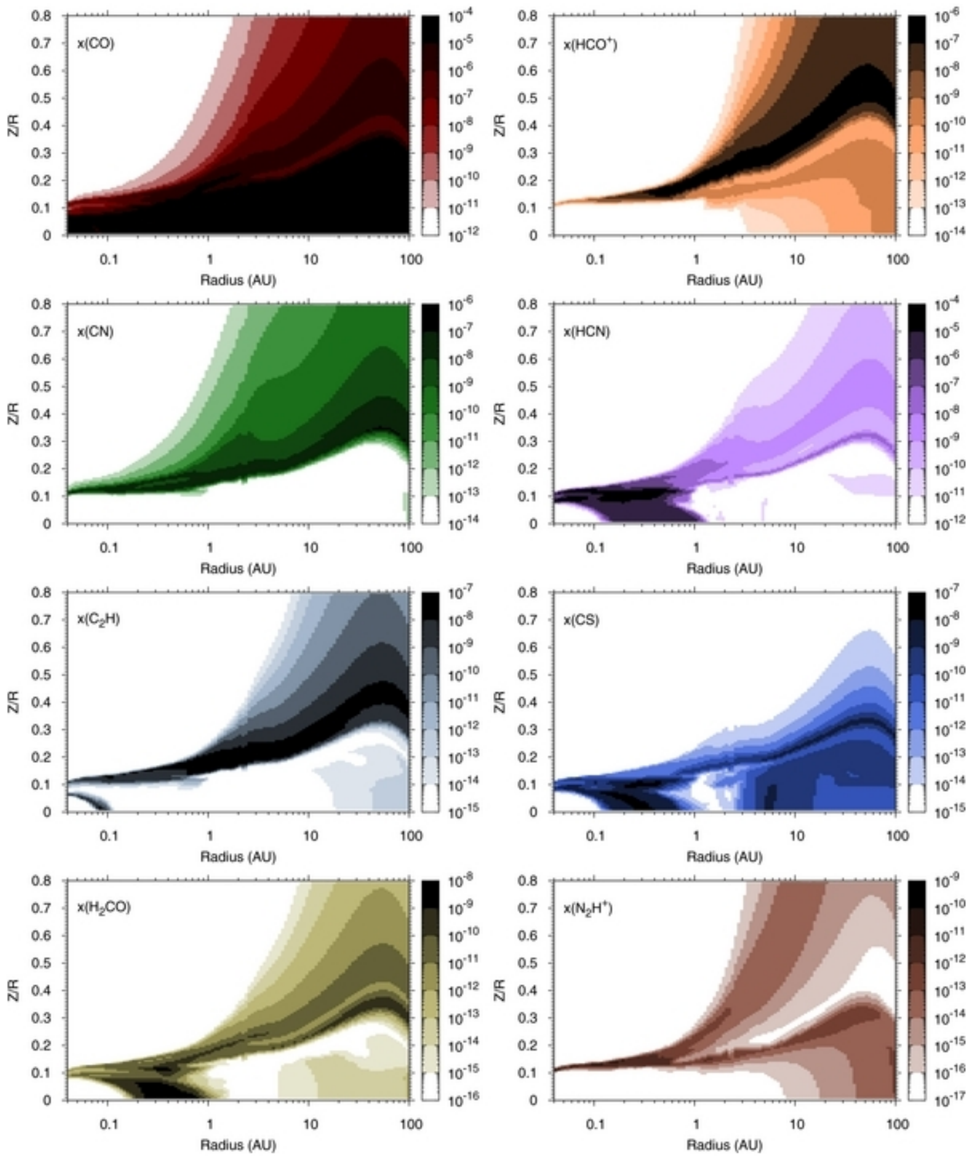
At 100 AU, mid-plane gas temperature = 70 vs 30 K; surface gas temperature = 1400 vs 180 K

Density distribution is also different between disks

At 100 AU:
Surface UV flux enhanced by about 100 but mid-plane is effectively shielded even in irradiated disk

Surface X-ray flux and X-ray ionisation rate are reduced by an order of magnitude in irradiated disk due to increased extinction from stellar radiation. In mid-plane CRs dominate ionisation

Molecular abundances in the proplyd



Mid-plane:

Very low flux of UV and X-rays below Z/R = 0.1 throughout the disk

Molecules with low binding energies, e.g. CO, remain in the gas phase throughout the disk (Td > 30 K out to 100 AU) with a relatively constant abundance, ~ $10^{-4} – 10^{-5}$

Molecules with large binding energies, e.g. HCN, remain frozen out throughout the disk down to 1 AU. Thermal desorption gives a high abundance (~ 10^{-5}) inside 1 AU.

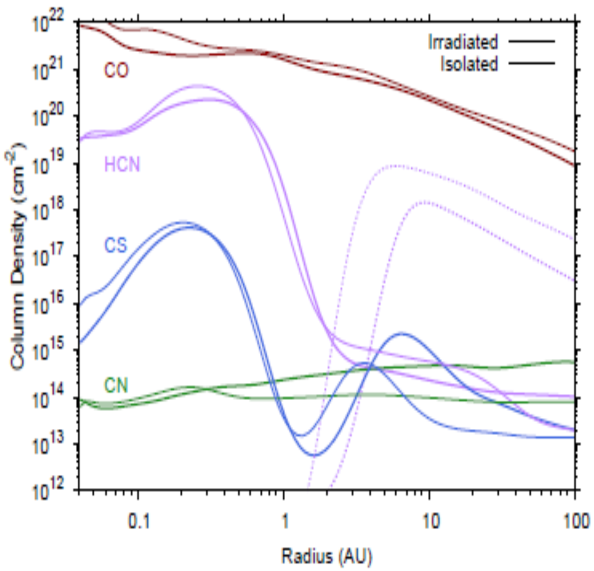
Warm Molecular Layer:

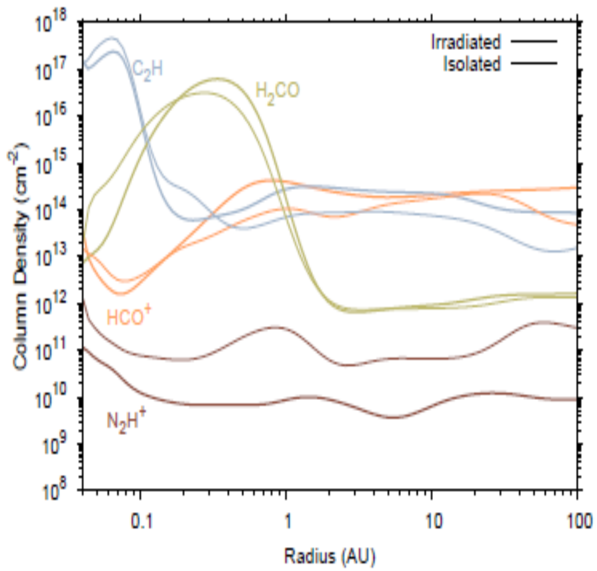
Radical layer, e.g. CN, C_2H, CS. Thinner and deeper, Z/R < 0.3, in the proplyd than in isolated disk models, Z/R = 0.3-0.5.

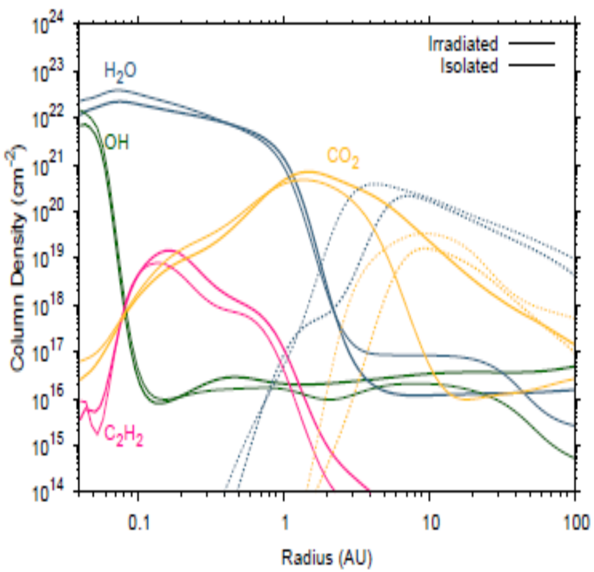
HCO^+ most abundant, ~ 10^{-7}, slightly above the warm molecular layer, N_2H^+ not very abundant throughout the disk as it is destroyed by abundant CO and by electrons.

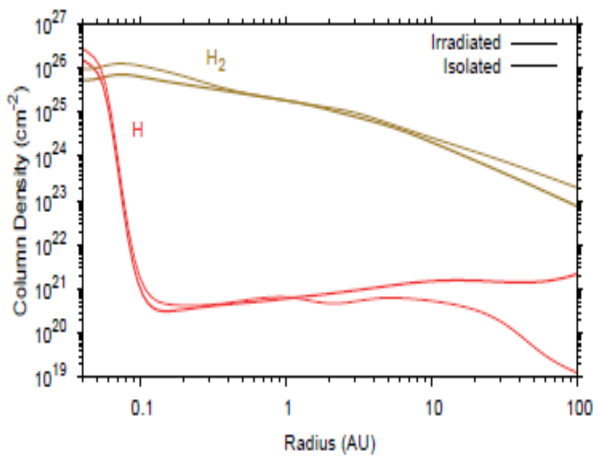
Some hints of truncation in abundances beyond 50 AU (although photo-evaporation may play a role at these radii).

Vertical Column Densities









Despite high UV flux, proplyd is **molecular**

Column densities for many species agree to within a factor of three in the irradiated vs isolated disk.

Some important exceptions in irradiated disk:

N_2H^+ less by about 10 throughout disk.

H_2O less abundant beyond 4 AU (factor of 7 at 10 AU) – OH/H_2O larger, indicative of enhanced photodissociation of H_2O.

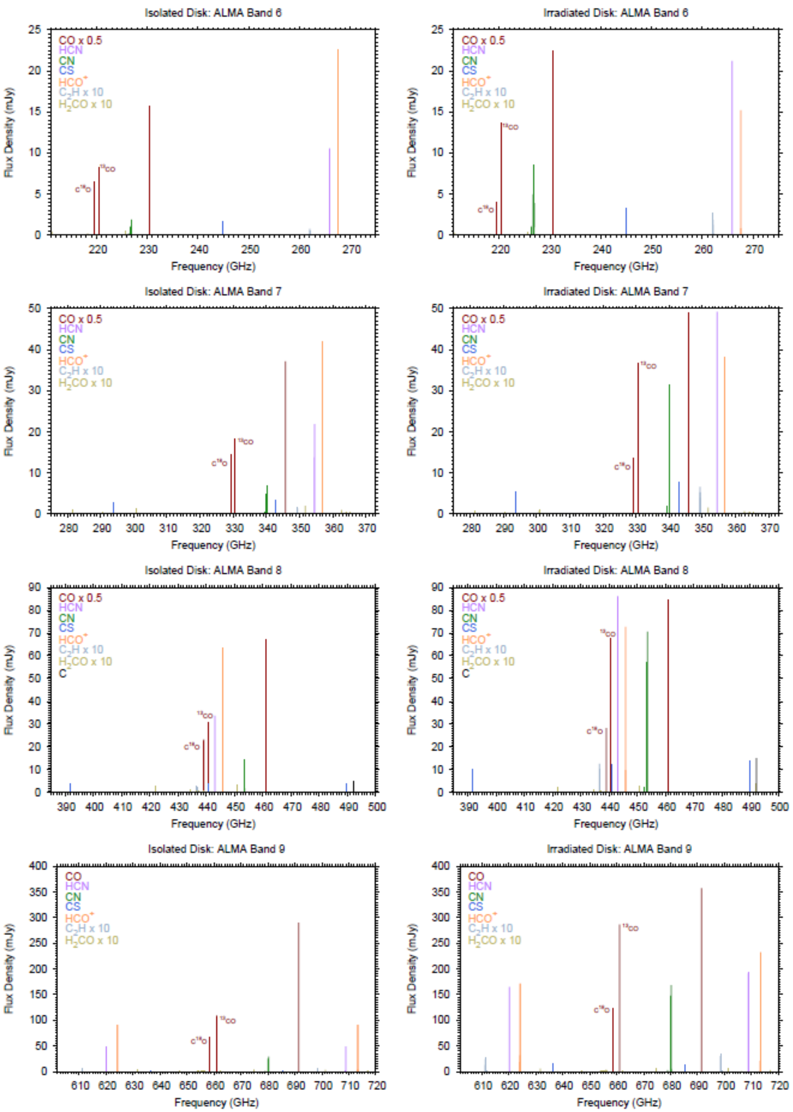
CS more abundant beyond 4 AU (factor of 40 at 10AU).

CO_2 more abundant beyond 1 AU (factor of 1800 at 10 AU).

Such increased abundances generally reflect the fact that snowlines move closer to the star in the irradiated disk.

Larger H/H_2 ratio beyond 5 AU also affects chemistry, particularly of OH and H_2O, in warm (~ 200K) gas (Glassgold et al. 2009, ApJ, 701, 142) $OH/H_2O > 1$ beyond 3-4 AU.

ALMA Emission Line Intensities



Isolated Irradiated

Band 6

Disk integrated line intensities for disk radius 100 AU at distance of 400pc.

Band 7

In general, higher gas temperatures in the irradiated disk result in higher peak intensities – not true for HCO^+ in Bands 6 and 7

Band 8

CI transitions at 492 and 809 GHz stronger by a factor of 2-4

Band 9

Significant portion of the CO, ^{13}CO and $C^{18}O$ ladders should be observable with ALMA, as may high frequency transitions of HCO^+, HCN and CN (integrated line strengths > 100 mJy km s^{-1}).

Summary

• Disk mid-plane is shielded even from enhanced radiation field

• Temperature of gas and dust in irradiated disk larger than those in isolated disk

• Disk is molecular – at least out to 100 AU – CO is not frozen out

• Strongly bound molecules remain on grains until ~ few AU – icy planetesimals may form in proplyds

• Rotational lines from simple species may be observable with ALMA – give information on physical conditions

Caveats:

• We have not considered effects of scattered UV photons incident on the back side of the disk – structure, chemistry and line emission

• We have not considered the effect of the disk wind on the structure and chemistry

• Line strengths calculated using LTE