Modelling of high-energy ionization processes in the circumstellar environment of young solar-like stars

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COSMIC RAYS - the salt of the star formation recipe

Florence, May 4, 2018

SEVENTH FRAMEWORK PROGRAMME

DiscAnalysis DIANA

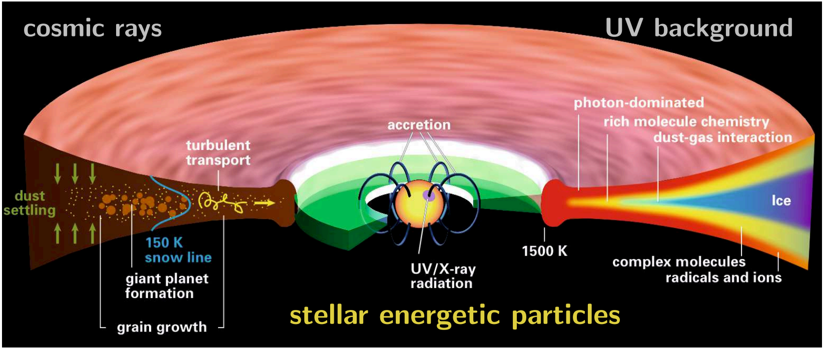
NWO Netherlands Organisation for Scientific Research

FWF Der Wissenschaftsfonds.

Outline/Introduction

Apply the radiation thermo-chemical disk model **ProDiMo** to study the role of **stellar energetic particle (high-energy) ionization** in

1. **Protoplanetary disks** (T Tauri, Class II) Paper: Rab et al. (2017)



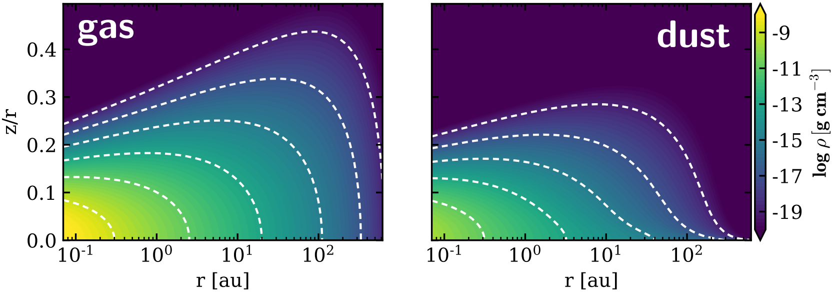
Credit: *Henning & Semenov (2013)*

2. **embedded sources** (Class 0/I) - first results

Goal: **observational constraints on SP fluxes in young stars**

Representative T Tauri disk model

Structure

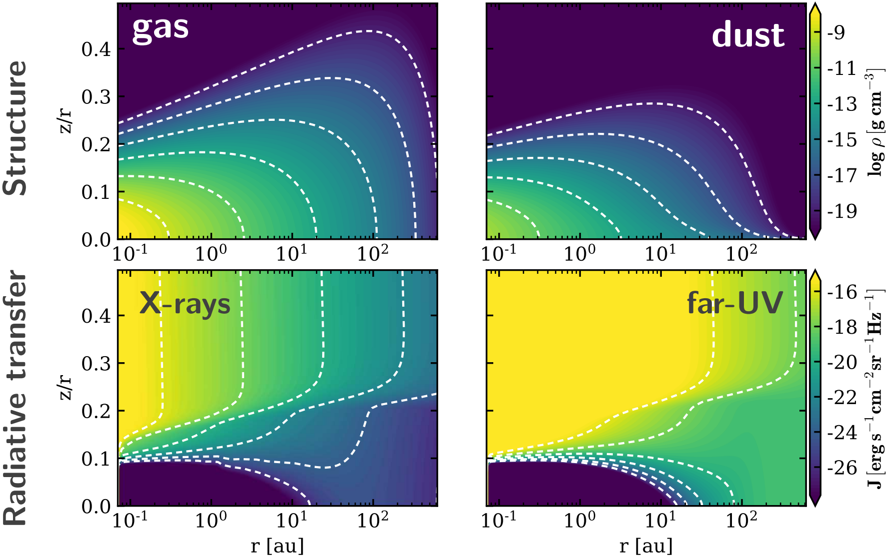


- **Stellar properties**
  $M_* = 0.7 M_\odot$
  $L_* = 1 L_\odot$
  $L_{\rm FUV} = 10^{-2} L_*$
  $L_{\rm X} \approx 10^{-3} L_* (= 10^{30}\,{\rm erg\,s^{-1}})$

- **Disk properties**
  $M_{\rm disk} = 10^{-2}\,M_\odot$
  total gas/dust= 100

Woitke+ (2009); Kamp+ (2010); Thi+ (2011); Aresu+ (2011); Woitke+ (2016); Rab+ (2017b,a, 2018)

Representative T Tauri disk model



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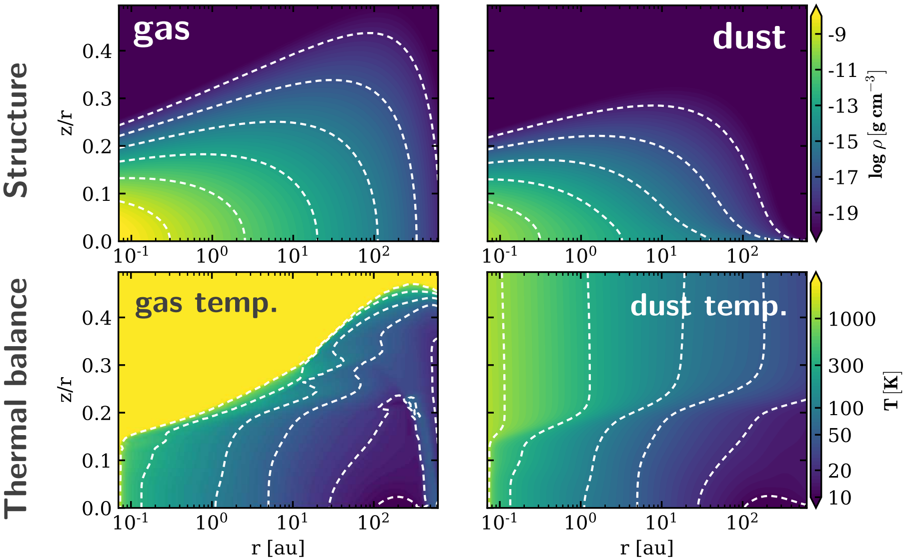

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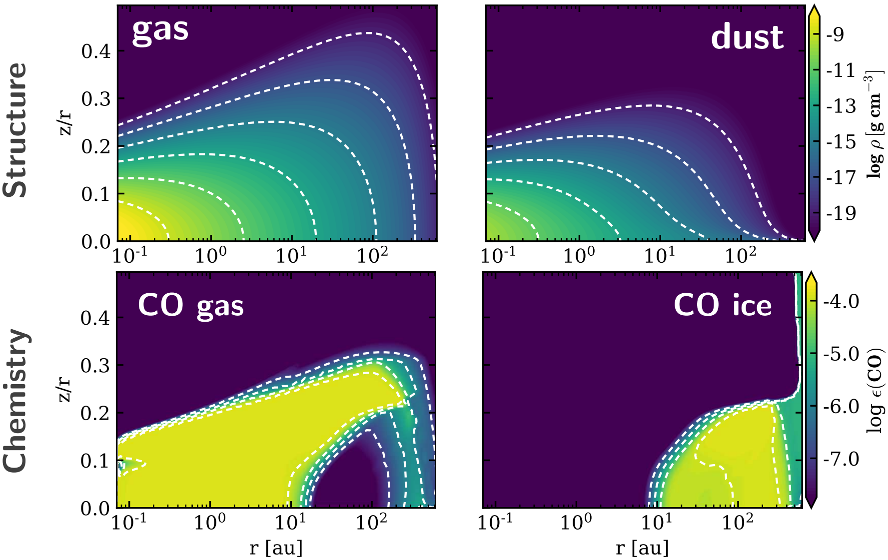

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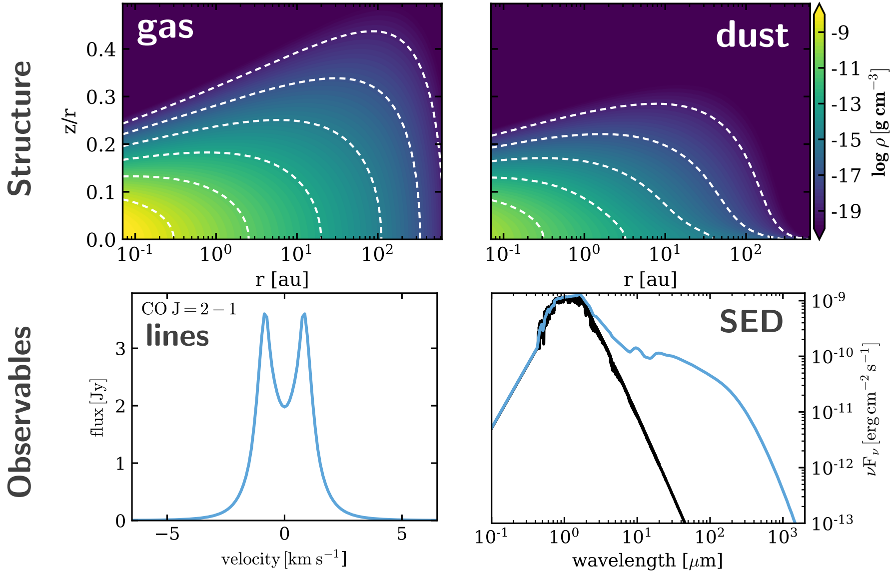
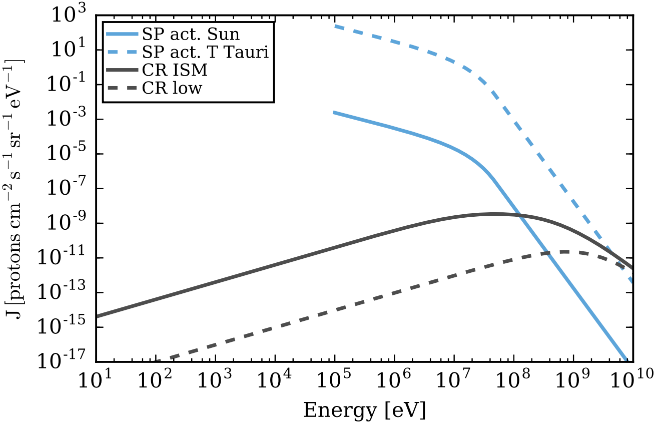
Representative T Tauri disk model



Woitke+ (2009); Kamp+ (2010); Thi+ (2011); Aresu+ (2011); Woitke+ (2016); Rab+ (2017b,a, 2018)

Stellar energetic particles (SP)

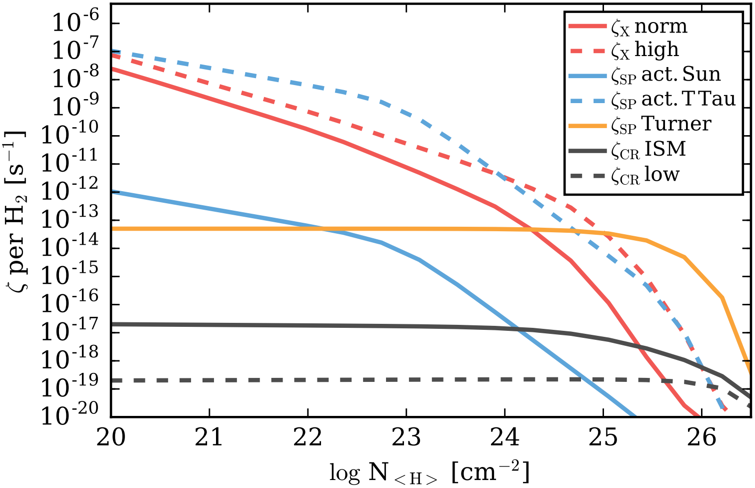


- **Active Sun:** averaged measurement of flare event (Mewaldt+ 2005) particle flux $\mathrm{F_p(E > 10MeV) \approx 150\,particles\,cm^{-2}\,s^{-1}}$ at 1 au
- **Active T Tauri:** $\gtrsim 10^5$ higher (Feigelson+ 2002; Ceccarelli+ 2014; Gounelle+ 2006)
- **Assumptions:** SPs are coming from the star; they reach the disk; average/continuous flux; treat them like galactic CRs for the chemistry; no magnetic fields

H_2 ionization rates

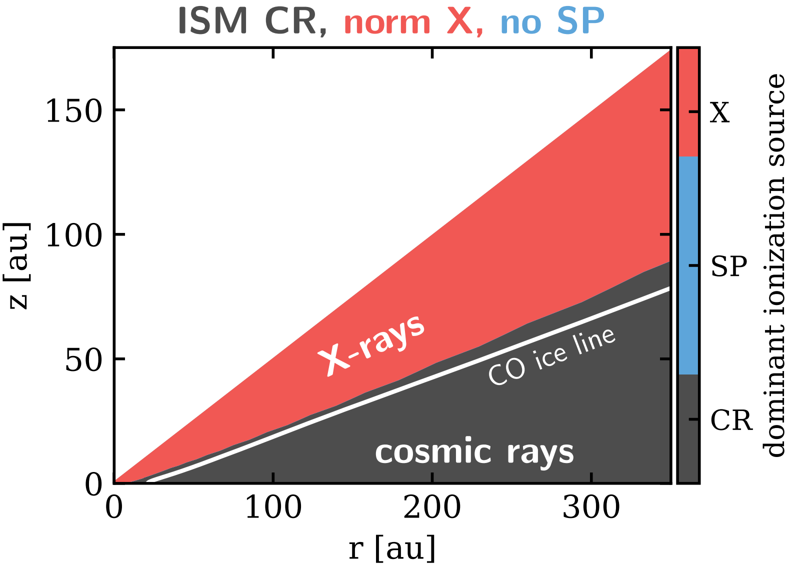
- **X-rays**: X-ray RT with scattering, gas & dust opacities (see **Rab+ 2018**)
  normal: typical T Tauri spectrum ($L_X = 10^{30}\,\mathrm{erg/s}$)
  high: $L_X = 5 \times 10^{30}\,\mathrm{erg/s}$ and harder
- **Stellar Particles**: continuous slowing-down approximation
  (**Marco** did that for us!)
  active Sun
  active T Tauri
- **Cosmic Rays**: consider CR absorption
  ISM ($\zeta_{CR} \approx 10^{-17}\,\mathrm{s}^{-1}$): ISM like Padovani+ (2009)
  low ($\zeta_{CR} \approx 10^{-19}\,\mathrm{s}^{-1}$): modulated (absorbed) spectrum Cleeves+ (2013)

H_2 ionization rates

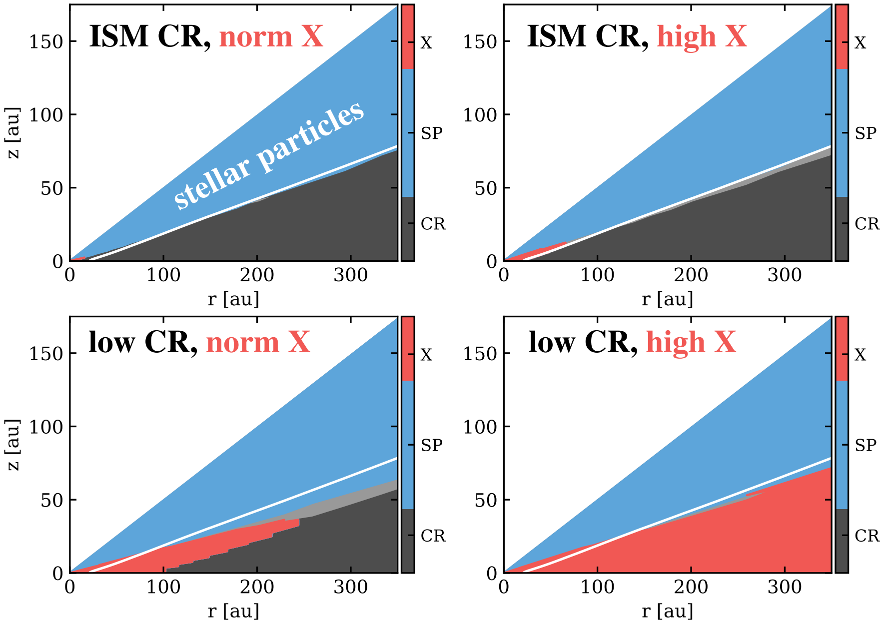


- 1D scenario for typical column densities in disks
- in Turner & Drake (2009) ζ_{SP} is a scaled version of ζ_{CR}

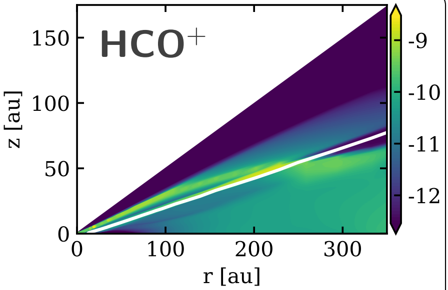
Dominant H_2 ionization source

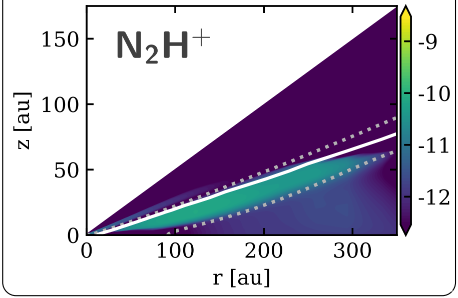


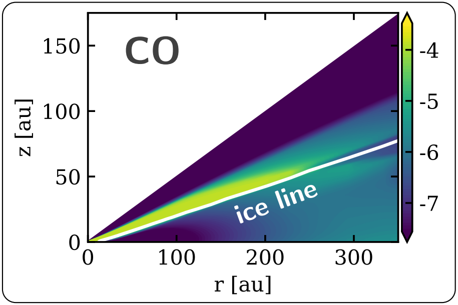
Dominant H_2 ionization source with SPs



molecular abundance structure (ISM CR, norm X, no SP)



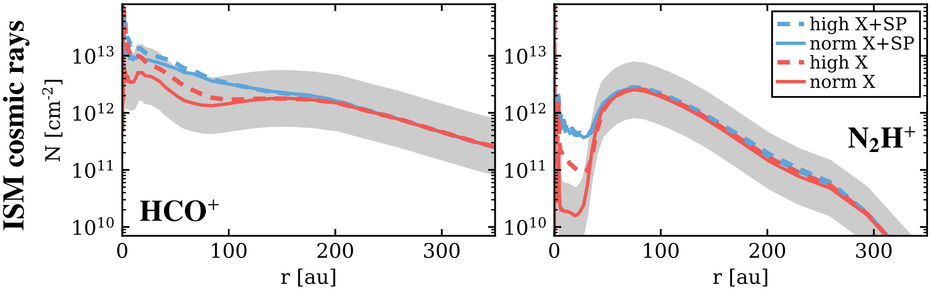




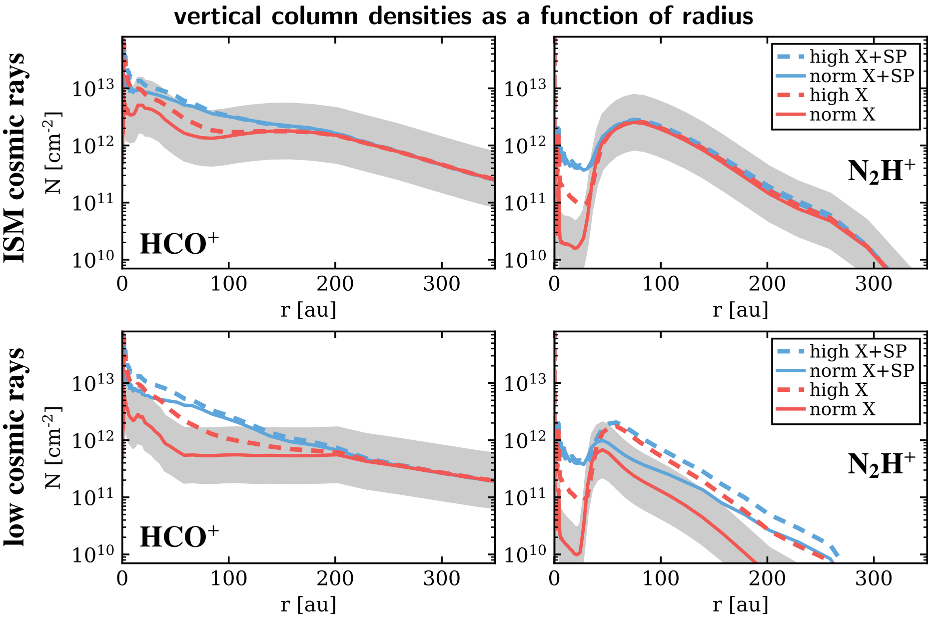
- molecular ion chemistry driven by high energy ionization of H_2
- HCO^+ & N_2H^+ common disk ionization tracers (observable)
- trace different regions of the disk as CO destroys N_2H^+ (CO snow line tracer Qi+ 2013)

Impact on molecular ions

vertical column densities as a function of radius

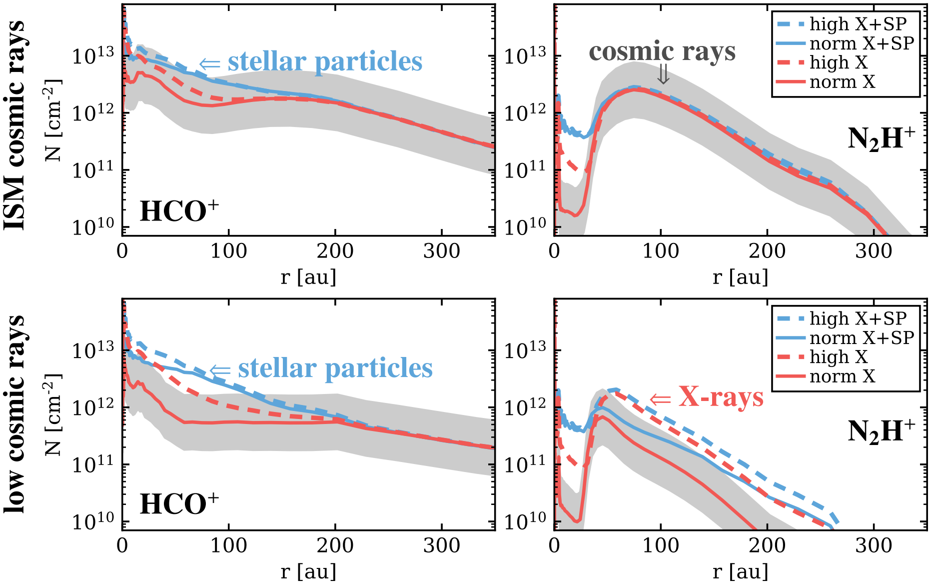


Impact on molecular ions



Impact on molecular ions

vertical column densities as a function of radius



HCO$^+$ & N$_2$H$^+$ J=3-2 ALMA simulations

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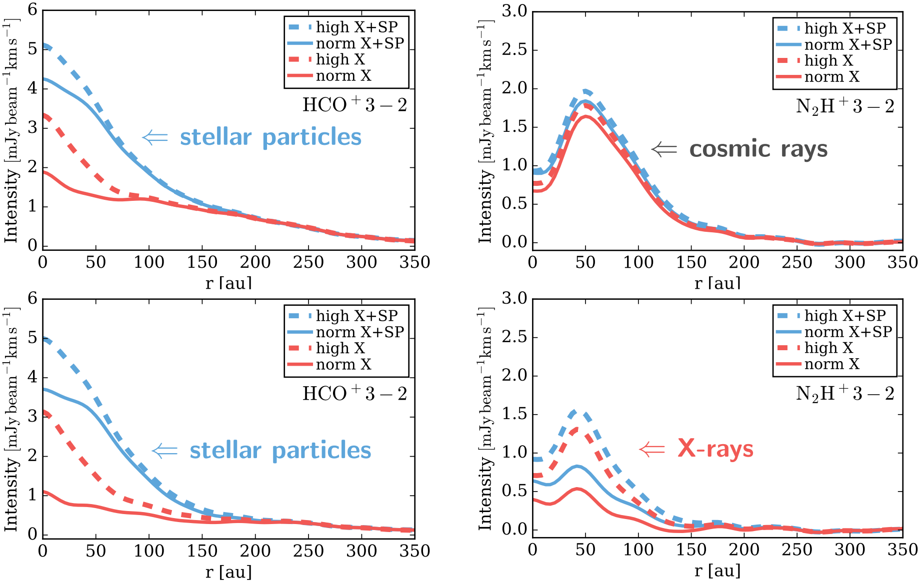
Radial line intensity profiles

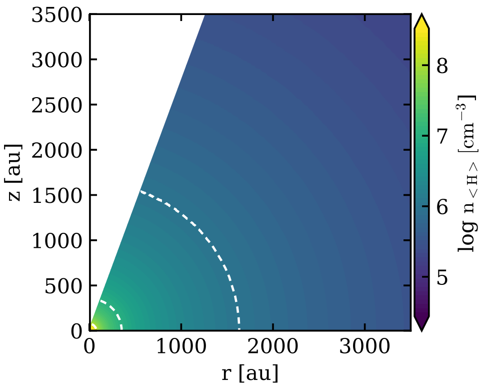


ALMA Sim. 40×12m; Integration: 3 h; Beam: ≈ 0.3"; distance: 140 pc; inclination 45°

Motivation: low HCO^+/N_2H^+ line/abundance ratios in **OMC-2 FIR 4** indicate high ionization rates (SP) (Ceccarelli+ 2014)

2D envelope structure (+outflow cavity)

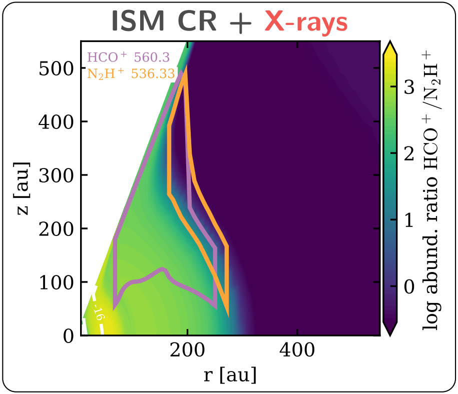
- based on 1D Class 0/I model of Visser+ (2015)
- full ProDiMo model (i.e. CR, X-rays, SP)
- T Tauri SP input spectrum
- is not OMC-2 FIR 4

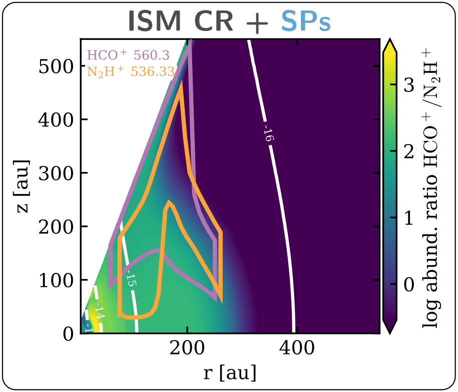


also rotating envelope model + disk is possible; see **Rab+ (2017a)**

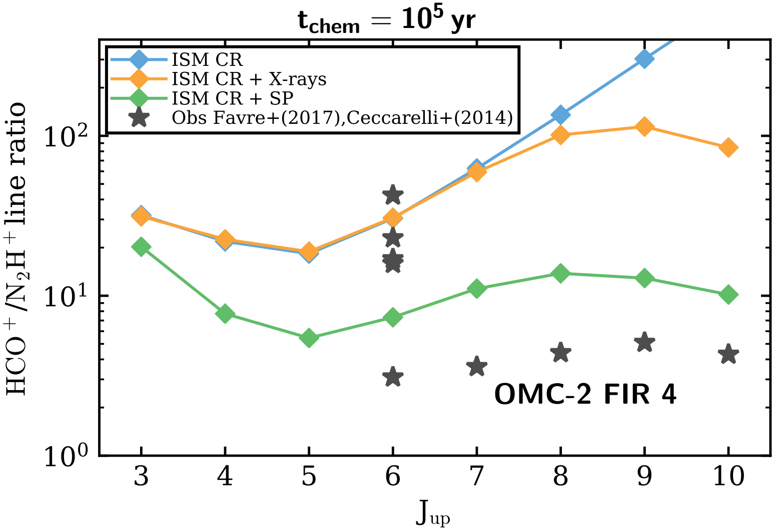
X-rays versus SPs

line origins for **HCO^+** and **N_2H^+** **J = 6 − 5**



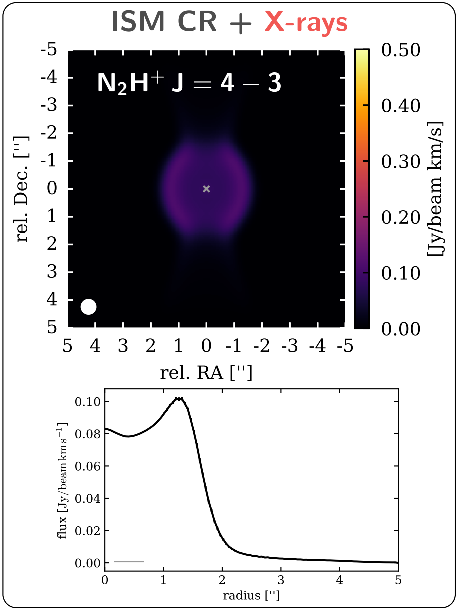


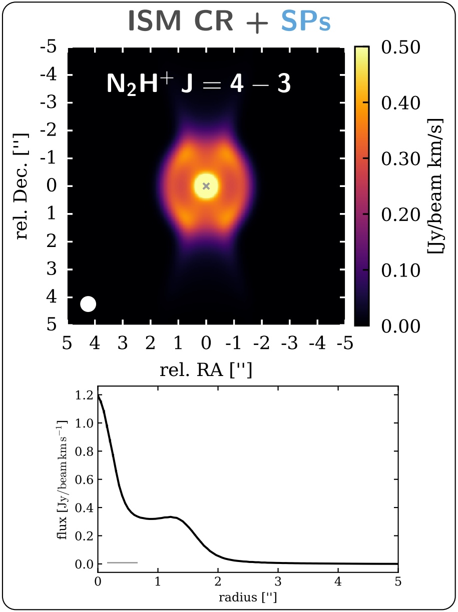
- X-rays don't penetrate deep into the envelope but SP do
- high ζ_{H_2}: N_2H^+ abun. increases within the CO snow line ($T \gtrsim 25$ K)
- **qualitatively consistent with Ceccarelli+ (2014)**



Model consistent with Herschel data (deviations? ζ_{SP}, chemistry)

What about ALMA?





ALMA Sim. Beam: 0.5''; distance: 200 pc; inclination 90°; see Anderl+ (2016) for N_2H^+ rings

Conclusions & Outlook

- SP flux in T Tauri stars can be constrained by spatially resolved observations of molecular ions tracing different regions of the disk (i.e. HCO^+, N_2H^+, DCO^+)
- first model with SPs in embedded sources are roughly consistent with Herschel data; sub(mm) observations can provide additional constraints

Outlook

- improve SP model (e.g. magnetic fields, variability, spectrum)
- explore parameter space (e.g. stellar properties, structure ...)
- use the model as a **testbed** to infer **observational signatures** of different particle **transport models** (e.g. Rodgers-Lee+ 2017; Fraschetti+ 2018) and particle **acceleration sites** (e.g. jets Padovani+ 2016)

Interested in ProDiMo ?

Contact me (rab@astro.rug.nl), I. Kamp or P. Woitke

Thank You for Your Attention!

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