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# Constraining the stellar energetic particle flux in young solar-like stars

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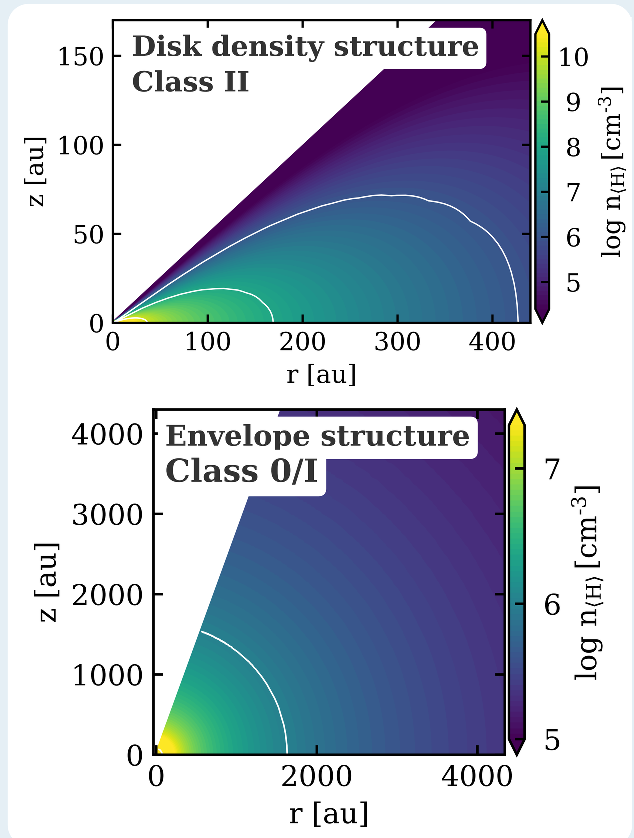
## Abstract

Anomalies in the abundance measurements of short lived radionuclides in meteorites indicate that the protosolar nebulae was irradiated by a large number of energetic particles ($E \gtrsim 10$ MeV), often called solar cosmic rays . The particle flux of the contemporary Sun cannot explain these anomalies. However, similar to T Tauri stars the young Sun was more active and probably produced enough high energy particles to explain those anomalies. However, the stellar particle flux (SP) of young stars is essentially unknown.
We model the impact of high-energy ionization sources on the chemistry of the circumstellar environment (i.e. disks and/or envelopes). The model includes X-ray radiative transfer and makes use of particle transport models to calculate the individual molecular hydrogen ionization rates in the disk. We study the impact on the chemistry via the ionization tracers $HCO^+$ and $N_2H^+$.
We argue that spatially resolved observations of those molecules combined with detailed models allow for disentangling the contribution of the individual high-energy ionization sources and to put constraints on the SP flux in young stars.

## Method

- use representative static 2D gas/dust density structures for Class II & Class 0/I objects (Rab et al. 2017a, see Fig. r.h.s)
- solve consistently for the radiation field, dust & gas temperature, the chemistry (chemical abundances) and produce synthetic observables with the radiation thermo-chemical code ProDiMo (e.g. Woitke et al. 2016; Kamp et al. 2017)
- X-ray radiative transfer including scattering (Rab et al. 2018) and particle transport models for SP and cosmic rays (Padovani et al. 2009; Rab et al. 2017b)
- assume SP flux for T Tauri stars $10^5$ times higher than the active Sun as proposed in the literature (e.g. Feigelson et al. 2002)
- vary stellar X-ray luminosity & cosmic-ray (CR) fluxes




## Results Class II/Disk

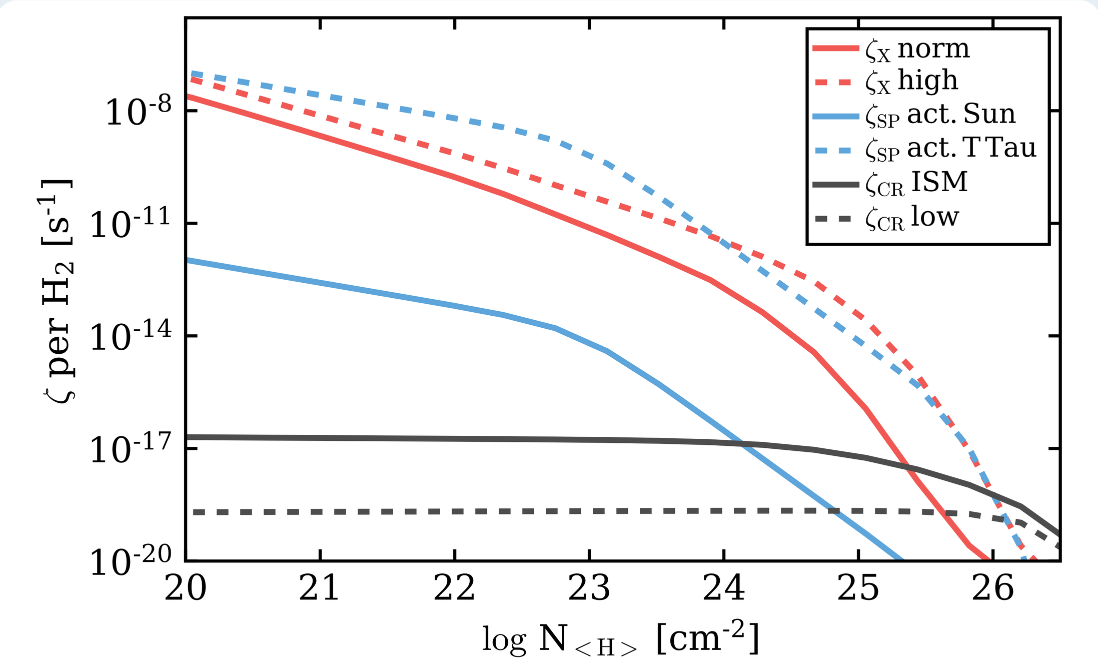



*Fig. 1: $H_2$ ion. rates $\zeta$ as a function of column density*

- high energy ionization sources drive ion chemistry via ionization of molecular hydrogen ($H_2$)
- wide range ($\approx$ 12 orders of magnitude) of possible $H_2$ ionization rates in protoplanetary disks (Fig. 1)
- we also consider the case of suppressed CR ionization rates due to the presence of a Helio(T Taurio)sphere ($\zeta_{CR}$ low $\approx 10^{-19}\,s^{-1}$, Cleeves et al. 2015)

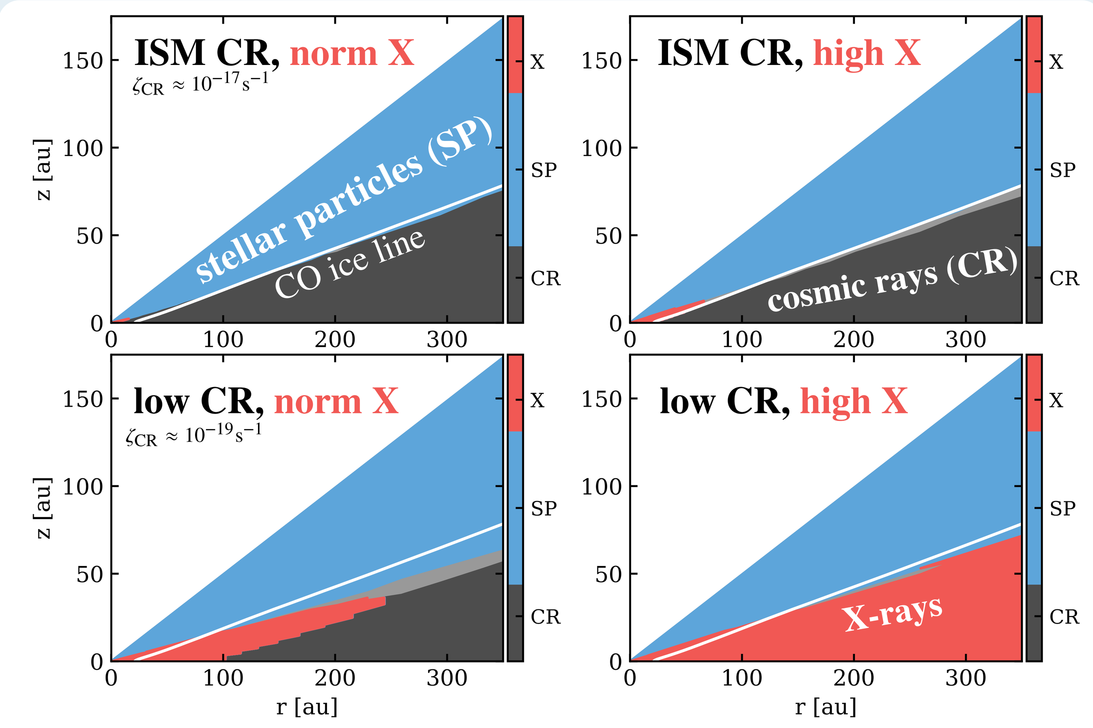



*Fig. 2: Dominant ionization source throughout the disk*

- cosmic rays (CR) are dominant in the disk midplane but X-rays can take over in case of suppressed CRs and/or for enhanced X-ray luminosities (e.g. flares)
- due to their high energies SPs are not scattered and travel along straight(radial) paths → SPs cannot penetrate to the midplane due to high radial column densities ($> 10^{25}$cm$^{-2}$) in the inner disk

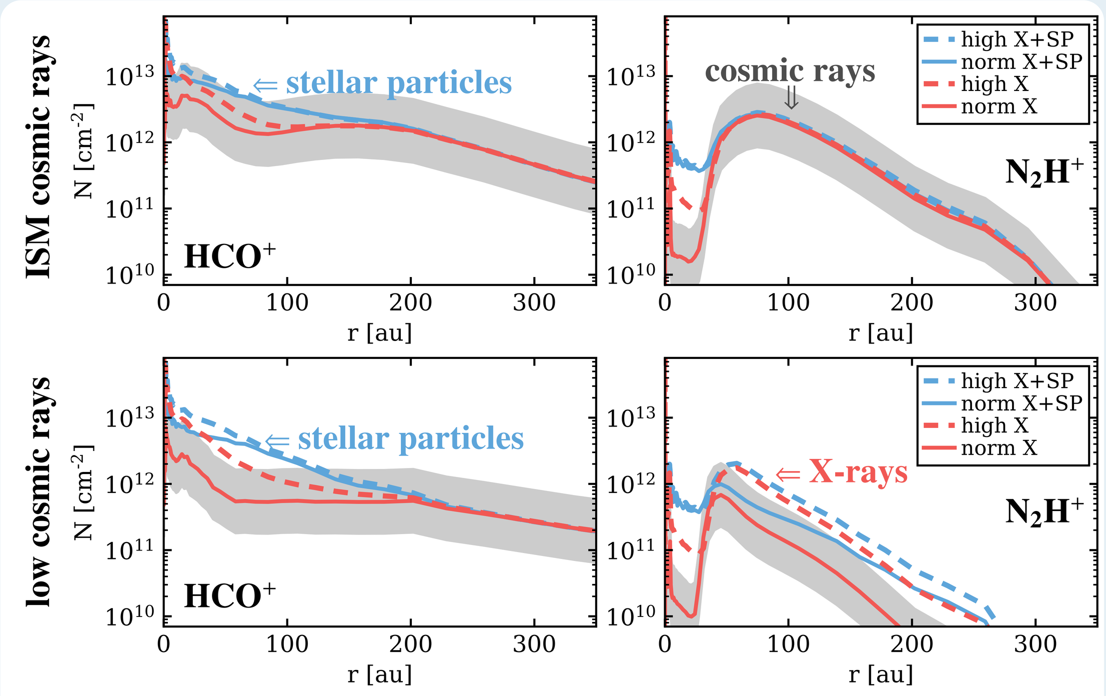
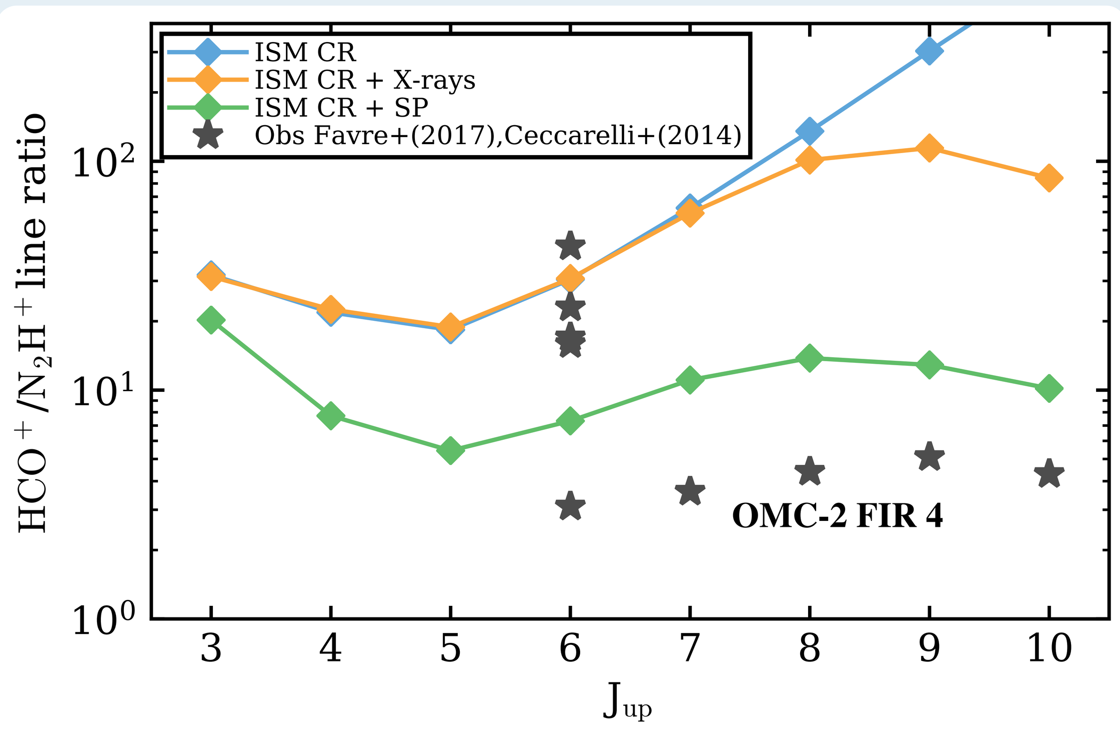


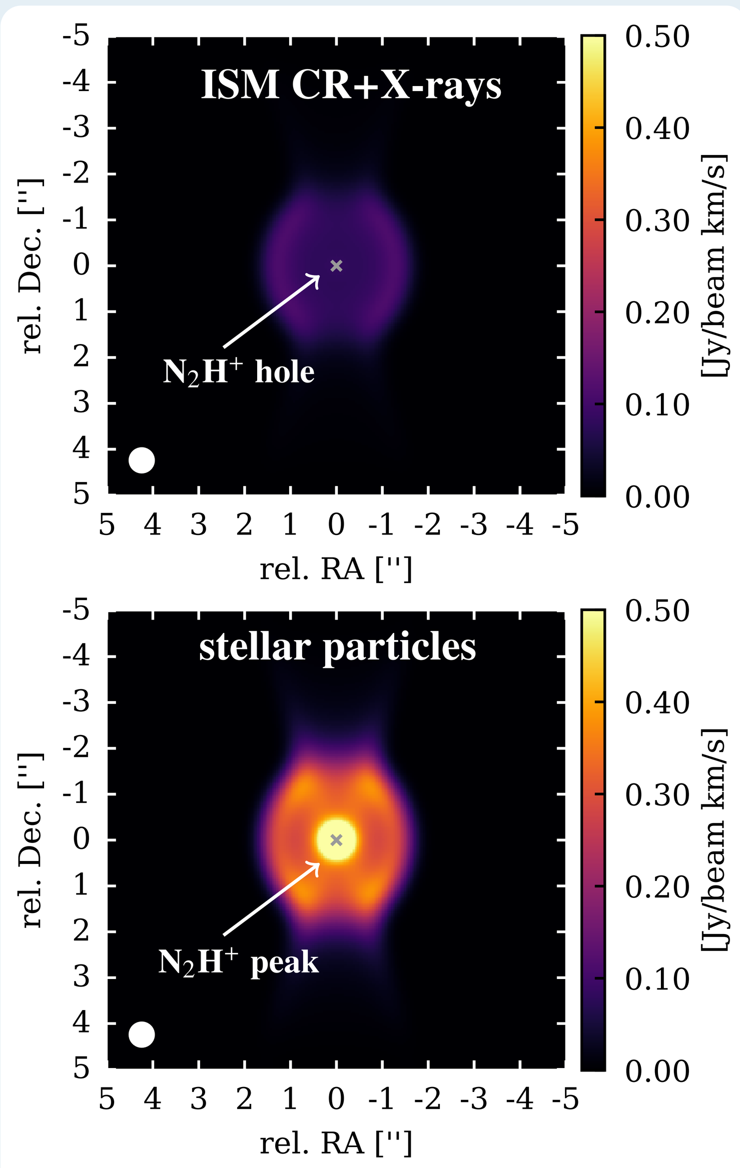

*Fig. 3: Impact on molecular column densities*

- $N_2H^+$ is efficiently destroyed by gaseous CO and resides mainly below the CO ice line (disk midplane); $HCO^+$ traces regions with gaseous CO (upper disk layers)
- $HCO^+$ mores sensitive to SP ionization; $N_2H^+$ mostly affected by CRs and X-rays (Fig. 3)
- simultaneous observations of both molecules allow to constrain the contribution of SP ionization

## Results Class 0/I




- low $HCO^+/N_2H^+$ line ratios measured in OMC-2 FIR 4 indicate high SP ionization rates of $\zeta_{SP} \approx 10^{-14}$–$10^{-12}\,s^{-1}$ (Ceccarelli et al. 2014)
- our representative Class 0/I model reproduces the impact of SPs on line ratios qualitatively (top Fig.); the model is not yet optimized for OMC-2 FIR 4
- SPs are more efficient than X-rays as they can penetrate the whole envelope; (proto)stellar X-rays are already absorbed in the inner region close to the star
- spatially resolved observations with ALMA should clearly show the impact of SP ionization (Fig. r.h.s)




*synthetic ALMA $N_2H^+$ J=4-3 line images without (top) and with (bottom) SP ionization.*

## Conclusions

- in disks (Class II) the SP ionization rate can be constraint via spatially resolved observations of $HCO^+$ and $N_2H^+$ in combination with detailed modelling. This is also true for SP flux levels required to explain the abundance anomalies of short-lived radionuclides in meteorites
- in Class 0/I objects high ionization rates due to stellar energetic particles should produce centrally peaked $N_2H^+$ emission (resolvable with ALMA), whereas a central hole is expected in the absence of SPs due to efficient destruction by gas-phase CO
- for the future we plan to model more complex structures (disk+envelope), include different SP input spectra and also make use of more sophisticated transport models (e.g. magnetic fields)
- the model can be used as a testbed to infer observational signatures of different particle transport models (e.g. Fraschetti et al. 2018; Rodgers-Lee et al. 2017) and particle acceleration sites (e.g. jets Padovani et al. 2016)

For more details see **Rab et al. 2017** and stay tuned for new Class 0/I results!

### References

• Ceccarelli, C., et al. 2014, The Astrophysical Journal Letters , 790, L1 • Cleeves, L. I., et al. 2015, The Astrophysical Journal, 799, 204 • Feigelson, E. D., Garmire, G. P., & Pravdo, S. H. 2002, The Astrophysical Journal, 572, 335 • Fraschetti, F., et al. 2018, The Astrophysical Journal, 853 • Kamp, I., et al. 2017, A&A , 607, A41 • Padovani, M., Galli, D., & Glassgold, A. E. 2009, A&A , 501, 619 • Padovani, M., et al. 2016, A&A , 590, A8 • Rab, C., et al. 2017a, A&A , 604, A15 • Rab, C., et al. 2017b, A&A , 603, A96 • Rab, C., et al. 2018, A&A , 609, A91 • Rodgers-Lee, D., et al. 2017, MNRAS , 472, 26 • Woitke, P., et al. 2016, A&A , 586, A103

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