Impact of energetic particle events on the chemistry of planet-forming disks and their observational signatures

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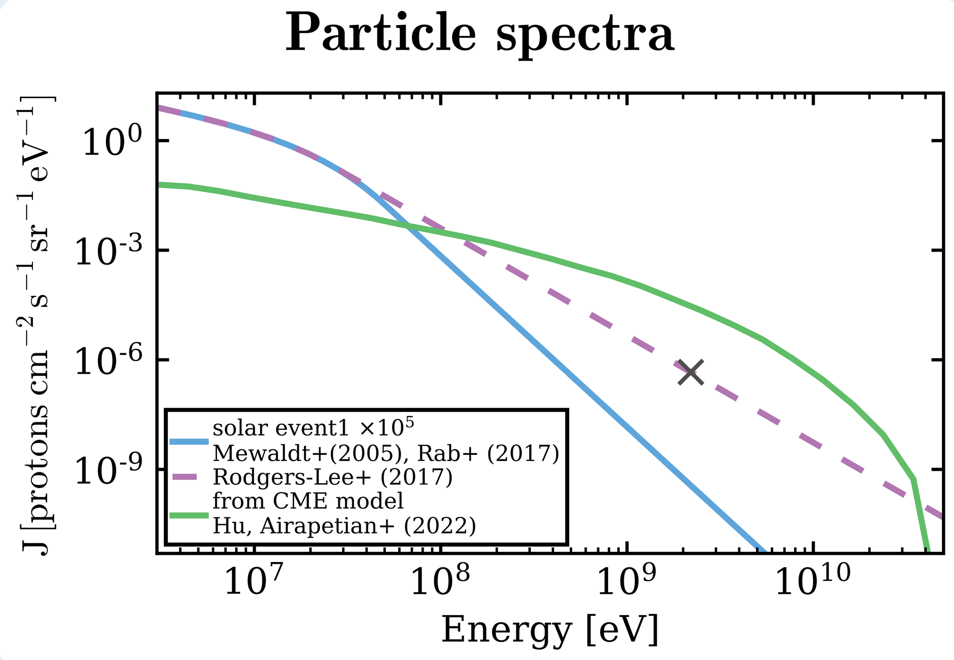
Context

- T Tauri stars show X-ray super/mega flares with total $E_X \gtrsim 10^{35}$ erg about once per week/month (e.g. Getman & Feigelson 2021)
- those events are likely related to coronal mass ejections (CMEs) capable of accelerating energetic particles (e.g. Hu et al. 2022)
- if stellar energetic particles (SP) reach the disk/envelope of T Tauri stars they are an efficient ionization source for H_2 and might be responsible for short-lived radionuclide anomalies observed in meteorites (e.g Gounelle et al. 2006)
- **Goal:** model impact of SP on ion chemistry in disks/envelops to constrain the particle flux of young stars via observations of molecular ions

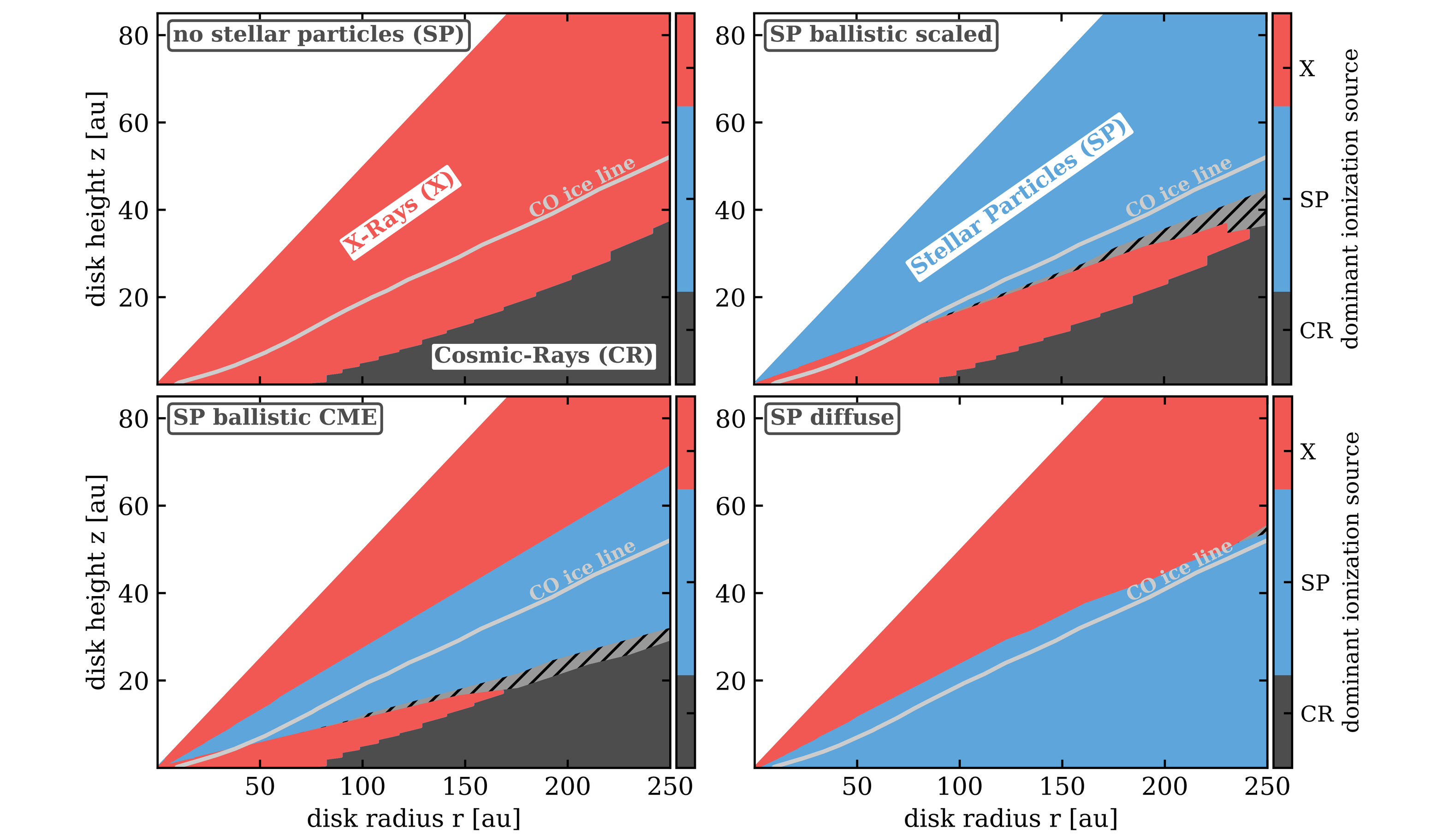
Method



- model the ionization due to high-energy sources (X-rays, galactic cosmic-rays (CR), stellar energetic particles (SP)) and the synthetic observables with the radiation thermo-chemical code ProDiMo (Woitke et al. 2009; Kamp et al. 2010; Thi et al. 2011; Rab et al. 2017, 2018)
- use different SP energy spectra (scaled from the Sun and from CME models; left Fig.)
- two particle transport models to calculate ionization rate: **ballistic:** continuous slowing-down approximation, particles travel on straight lines (e.g. Padovani et al. 2018); **diffuse:** diffusive propagation due to turbulent magnetic field (Rodgers-Lee et al. 2017).

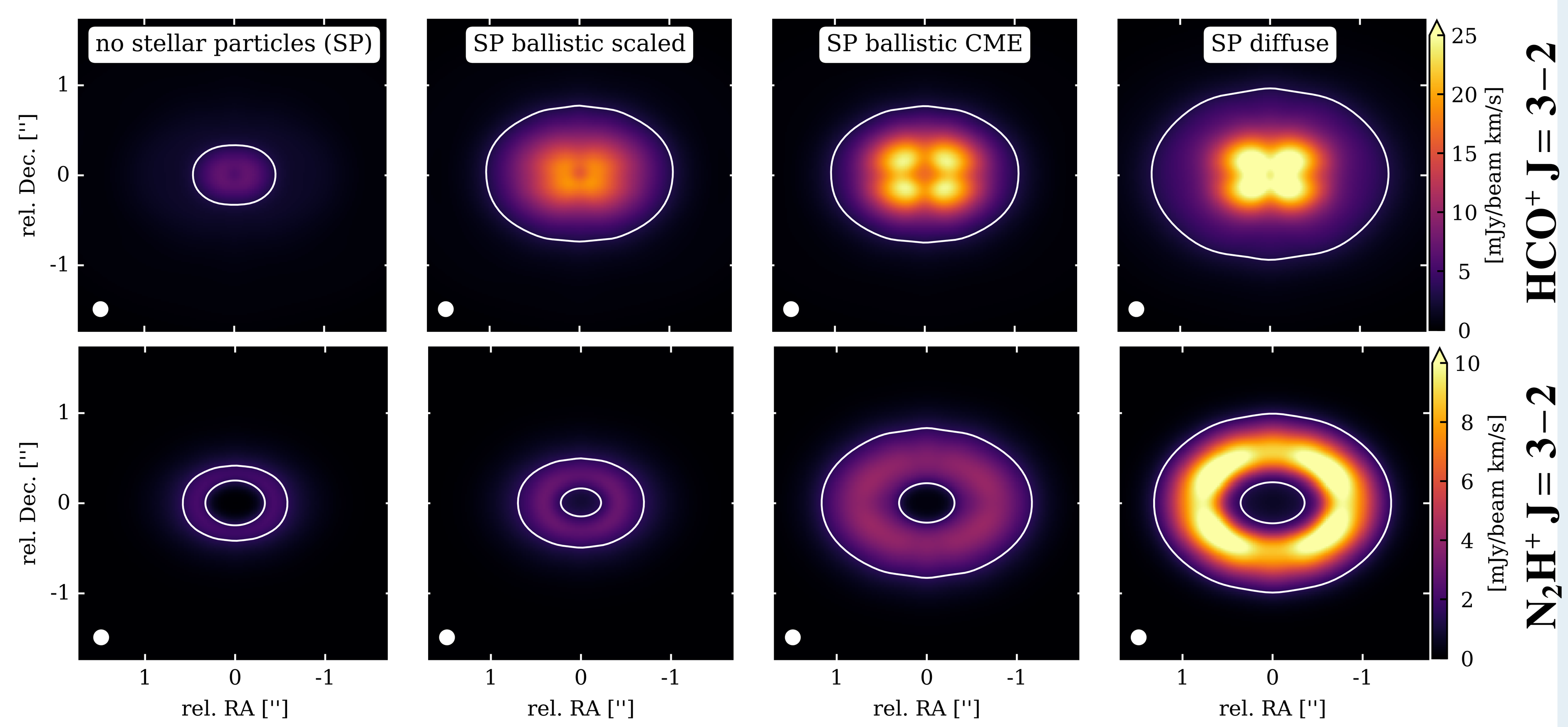
Results: planet-forming disk

Dominant H_2 ionization agent



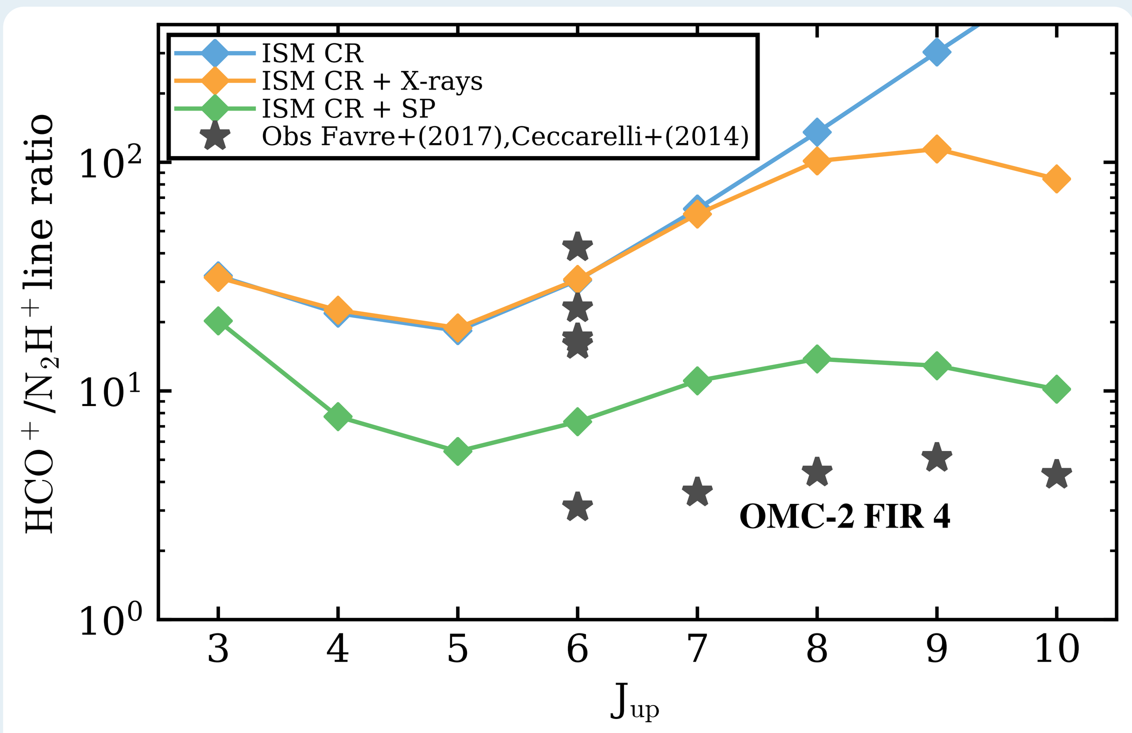
- dominant H_2 ionization agent in the disk, for models with a low galactic cosmic-ray (CR) ionization rate ($\zeta_{CR} \approx 10^{-19}\,s^{-1}$; Cleeves et al. 2013)
- depending on the shape of the SP spectra and the transport method (ballistic or diffuse) SPs dominate the H_2 ionization certain disk regions, assuming an enhanced particle flux of a factor of $\gtrsim 10^5$ higher compared to the contemporary Sun (Feigelson et al. 2002)

Synthetic Observables (Moment 0 maps)

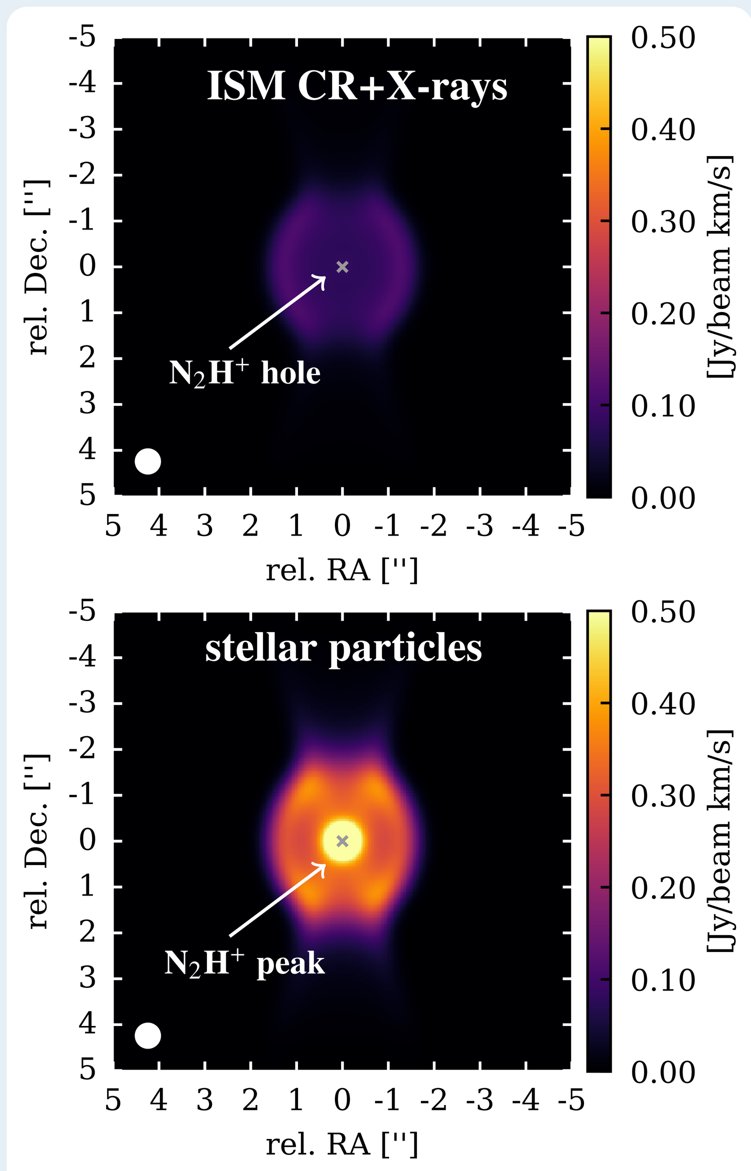


- synthetic observables (ALMA) for the models shown in the left Fig.
- HCO^+ and N_2H^+ trace different regions. N_2H^+ tracers deeper layers of the disk (below the CO ice line) as it is destroyed by gas phase CO
- observing both molecules allows to disentangle the contribution of the various ionization agents, to constrain the SP flux (see also Rab et al. 2017) and possibly also the dominant transport mechanism

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 simple spherical Class 0/I model reproduces the impact of SPs on line ratios qualitatively (top Fig.); the model is not 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

- impact of expected stellar particle flux observable in disks
- shape of particle energy spectrum & transport mechanisms are relevant
- detailed models are required to disentangle contribution of various high-energy ionization sources from observations
- simple envelope model roughly consistent with observations; spatially resolved observations should clearly show origin of particle acceleration (see also Cabedo et al. 2022)

Outlook

- modelling variability of flares and SPs (i.e. time-dependent)
- investigate different disk structures (transitional disks, gaps etc.)
- impact on other molecules (e.g. hydrocarbons) and solids (e.g. ice composition)
- consider jets as particle acceleration source (Padovani et al. 2016)

References

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